

# INFORMATYKA AUTOMATYKA POMIARY

W GOSPODARCE i OCHRONIE ŚRODOWISKA

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Kazakh National Technical University after K.I. Satpaev  
Institute of Information and Telecommunication Technology  
Automation and Control Department

# 50 LAT WYDZIAŁU ELEKTROTECHNIKI I INFORMATYKI POLITECHNIKI LUBELSKIEJ



Wizualizacja siedziby WEiI po rozbudowie

Wydział Elektrotechniki i Informatyki Politechniki Lubelskiej w 2014 roku obchodzi jubileusz 50-lecia działalności. Jednostka ta powstała w 11. roku działalności pierwszej uczelni technicznej w Lublinie, ówczesnej Wieczorowej Szkoły Inżynierskiej, jako jej drugi wydział. W ubiegłym roku Politechnika Lubelska świętowała 60-lecie istnienia. Obecnie w strukturze organizacyjnej Uczelni funkcjonuje sześć wydziałów: Elektrotechniki i Informatyki, Mechanicznego, Budownictwa i Architektury, Inżynierii Środowiska, Podstaw Techniki oraz Zarządzania.

W zeszłorocznej ocenie parametrycznej wydział uzyskał kategorię A, jako jeden z trzech w Politechnice Lubelskiej. Traktujemy tę okoliczność jako jeden z ważnych, obok jubileuszu, powodów do świętowania.

Obchody obejmują kilka wydarzeń, które mają na celu przedstawienie i promocję osiągnięć wydziału oraz planów na przyszłość w zakresie edukacji, rozwoju kadry i badań naukowych w środowisku inżynierów elektryków i informatyków. W okresie 50 lat działalności wydział wydał 8 731 dyplomów inżyniera i magistra inżyniera, w tym 7 715 w dyscyplinie elektrotechnika i 1 016 w dyscyplinie informatyka. Od czasu uzyskania praw doktorystowania w 1978 roku wypromowaliśmy 106. doktorów nauk technicznych, a od momentu uzyskania pełni praw akademickich w 2000 roku – 15. doktorów w dyscyplinie elektrotechnika uzyskało stopnie naukowe doktora habilitowanego. Obecnie kształcimy ponad 1100 studentów na kierunkach Elektrotechnika, Informatyka i wspólnie z Wydziałem Mechanicznym na kierunkach Mechatronika oraz Inżynieria Biomedyczna.

Jubileuszowe uroczystości rozpoczną się posiedzeniem Senatu PL w dniu święta Politechniki Lubelskiej – 13 maja 2014 roku. Dzień wcześniej, 12 maja 2014 roku, odbędzie się okolicznościowa konferencja pn. „Wydział Elektrotechniki i Informatyki kuźnią kadr dla przemysłu”, złożona z dwóch sesji: naukowo-edukacyjnej: „WEiI – wczoraj, dziś i jutro”, adresowanej do przyszłych kandydatów, studentów, absolwentów i pracodawców, oraz naukowo-dyskusyjnej: „Nauka i innowacje na WEiI PL dla przemysłu”, kierowanej do naukowców i przedstawicieli biznesu.

Piknik pracowników Politechniki Lubelskiej, organizowany tradycyjnie w ramach obchodów Święta Uczelni, w tym roku odbędzie się 13 czerwca 2014 roku i będzie mu towarzyszył zjazd absolwentów Wydziału Elektrotechniki i Informatyki PL.

50. inauguracja roku akademickiego 2014/2015 na Wydziale Elektrotechniki i Informatyki Politechniki Lubelskiej odbędzie się w październiku 2014 roku, a głównym punktem uroczystości będzie oddanie do użytkowania dobudowywanego ze środków MNiSW Wydziałowego Centrum Elektroniki, Optoelektroniki i Teleinformatyki.

W imieniu społeczności Wydziału Elektrotechniki i Informatyki, władz uczelnianych i wydziałowych oraz członków Rady Wydziału serdecznie zapraszam wszystkich absolwentów, byłych i obecnych współpracowników i sympatyków naszej jednostki na uroczystości 50-lecia.

Dziekan WEiI  
Prof. Henryka Danuta Stryczewska

# 1/2014

## styczeń-marzec

### WYDANIE

pod redakcją naukową

prof. dr hab. inż. Waldemara Wójcika

# INFORMATYKA AUTOMATYKA POMIARY

## W GOSPODARCE I OCHRONIE ŚRODOWISKA

Informatics Control Measurement in Economy and Environment Protection

KWARTALNIK CZĘŚCIOWO DOTOWANY PRZEZ MINISTERSTWO NAUKI I SZKOLNICTWA WYŻSZEGO

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## OD WYDAWCY

### Szanowni Czytelnicy,

oddajemy w Państwa ręce pierwszy w 2014 roku numer wydawanego przez CITT LPNT kwartalnika IAPGOŚ.

Gorąco polecamy artykuł profesora Waldemara Wójcika, prof. Batyrbeka Suleimenova, dr inż. Genadiya Shadrina, mgr inż. Mikhaila Shardina oraz mgr inż. Dmitriya Porubova na temat systemu automatycznego zarządzania zespołem samochodów z silnikami diesla. W artykule zostało rozpatrzone optymalne sterowanie procesem przemieszczania pojazdów z zastosowaniem złożonego kryterium, zależnego od zużycia paliwa i czasu przejazdu, ze zmiennymi współczynnikami modelu matematycznego fizycznego procesu, uwzględniając wpływ czynników zakłócających.

W numerze znajdą Państwo również artykuł prezentujący metodę syntezy trajektorii ruchu robota manipulacyjnego wg stopni swobody, autorstwa prof. Muhita Baybatshaeva oraz dr inż. Akambaya Beysembaeva.

Polecamy również kilka artykułów przedstawiający matematyczny opis systemu kontroli złożonego systemu dynamicznego na przykładzie grupy bezzałogowych samolotów autorstwa prof. Olega Mashkova oraz dr inż. Maksyma Korobchanskyia.

Miłośnikom modelowania matematycznego proponujemy artykuł omawiający wyniki badań dotyczące rozwiązań numerycznych punktowego modelu ułamkowego rzędu kinetyki neutronów oraz wymiany ciepła w reaktorze jądrowym.

Osoby zainteresowane modelowaniem przepływu ciepła na pewno nie ominą artykułu autorstwa prof. Alicji Piaseckiej-Belkhayat oraz mgr inż. Anny Korczak, dotyczącego dwuwymiarowego modelu numerycznego przepływu ciepła w ciele krystalicznym.

## RADA PROGRAMOWO-NAUKOWA

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## PROF. WALDEMAR WÓJCIK

**HONOROWYM PROFESOREM WSCHODNIOKAZACHSTAŃSKIEGO PAŃSTWOWEGO  
UNIWERSYTETU TECHNICZNEGO IM. D. SERIKBAYEVA (EKTU),  
UST-KAMENOGORSK, KAZACHSTAN**



Fot. 1. Prof. Nurlan Mukhanovich Temirbekov (rektor) i prof. Waldemar Wójcik podczas wręczenia tytułu profesora honorowego Wschodniokazachstańskiego Państwowego Uniwersytetu Technicznego im. D. Serikbayeva

W dniu 25 grudnia 2013 roku odbyła się w Ust-Kamenogorsku (Kazachstan) uroczystość nadania godności profesora honorowego Wschodniokazachstańskiego Państwowego Uniwersytetu Technicznego im. D. Serikbayeva prof. Waldemarowi Wójcikowi.

Prof. Waldemar Wójcik w lipcu 1975 roku ukończył studia magisterskie na Wydziale Elektroniki Politechniki Wrocławskiej. Będąc absolwentem specjalności telekomunikacja rozpoczął od 1 października 1975 roku pracę jako asystent w Zakładzie Automatyki i Pomiarów, kierowanym przez doc. dr inż. Tadeusza Latochę w Politechnice Lubelskiej zajmując się automatyzacją przemysłowych procesów technologicznych w ramach programu węglowego dot. racjonalnej gospodarki energią elektryczną. W latach 1981-82 odbył staż naukowy w Moskiewskim Instytucie Energetycznym, gdzie w Katedrze Automatyki u prof. Krupa pracował nad tematem poświęconym opracowaniu metod syntezy wielowymiarowego systemu regulacji liniowych obiektów stochastycznych. W sierpniu 1985 roku obronił pracę doktorską pt. „Komputerowa stabilizacja parametrów szlamu w procesie produkcji cementu” pod kierunkiem doc. dr inż. Tadeusza Latochę.

W tym czasie ośrodek lubelski intensywnie pracował nad zastosowaniem techniki światłowodowej w różnych dziedzinach gospodarki. Prof. W. Wójcik włączył się do pracy zespołu realizującego te zadania. Przez prawie dziesięć lat brał udział w ponad 20 pracach badawco-wdrożeniowych wykonywanych w ramach Centralnych Programów Badawczo-Rozwojowych (7 tematów) oraz zlecanych przez m.in. energetykę, górnictwo, banki, itp. W roku 1992 odbył staż w Politechnice Madryckiej w Katedrze Optoelektroniki, w ramach którego pracował w Parku Technologicznym w Zamudio k. Bilbao.

Po powrocie zajął się tematyką monitorowania procesów spalania w kotłach energetycznych. Od 1994 roku podjął scisłą współpracę z Elektrownią „Kozienice” SA, a od 1995 roku z Instytutem Energetyki w Warszawie. Współpraca z elektrownią zaowocowała kierowanymi przez niego czterema pracami badawczymi, których rezultaty zostały wdrożone oraz grantem celowym, którego był kierownikiem. Zakończył się on sukcesem w marcu 2002 roku, a dotyczy nowych konstrukcji aparatury

przeznaczonej do monitorowania pracy palników pyłowych i mazutowych w kotłach OP 650 i AP 1250. Rezultatem współpracy z Instytutem Energetyki był udział w grancie w ramach V programu Ramowego Unii Europejskiej pt. „Charakteryzacja zapłonu i przebiegu spalania mieszanek węgiel/paliwo wtórne poprzez pomiary w plomieniu turbulentnym w pomniejszonej skali (0,5 MWth)”. W 1997 roku rozpoczął współpracę z Katedrą Układów Elektronicznych Politechniki Lwowskiej. W ramach tej współpracy obronił w 2001 roku pracę habilitacyjną pt. „Metody kontroli parametrów cieplnych procesów spalania”, w której przedstawił główne rezultaty prac prowadzonych w Elektrowni „Kozienice”. Wyniki tych prac naukowo-badawczych, jako autor lub współautor, przedstawił w czterech monografiach, ponad 80 artykułach opublikowanych w materiałach konferencyjnych konferencji międzynarodowych i krajowych.

W wyniku realizacji prac badawczych utworzył w Katedrze Elektroniki grupę, która zajmuje się badaniami związanymi z zastosowaniem nowych konstrukcji optoelektronicznych do diagnostyki, sterowania i nadzoru procesu spalania w przemysłowych kotłach energetycznych. W wyniku prowadzonych prac badawczych z tego zakresu 9 członków zespołu zrealizowało prace doktorskie, jedna uzyskała stopień doktora habilitowanego, a Waldemar Wójcik w 2009 roku otrzymał tytuł profesora nauk technicznych.

Prof. W. Wójcik łączy pracę naukową i dydaktyczną z działalnością organizacyjną i społeczną. W latach 1999-2005 (dwie kadencje) pełnił funkcję prodziekana ds. kształcenia na Wydziale Elektrycznym Politechniki Lubelskiej, a następnie przez dwie kadencje (2005-2012) był dziekanem tego wydziału. Był m.in. inicjatorem stworzenia Lubelskiego Parku Naukowo-Technologicznego, budowy Centrum Elektroniki, Automatyki i Teleinformatyki Wydziału Elektrotechniki i Informatyki Politechniki Lubelskiej, czy też współzałożycielem i przewodniczącym rady naukowo-programowej czasopisma Pomiary, Automatyka, Komputery w Gospodarce i Ochronie Środowiska (obecnie IAPGOŚ).

W jego działalności istotne są związki z Ukrainą, Białorusią, Rosją, a w ostatnim czasie także z Kazachstanem. Jego aktywność

naukowa zaowocowała m.in. włączeniem Go w 2001 roku w skład kolegium redakcyjnego czasopisma „Optoelectronic Information – Power Technologies” wydawanego w Winnicy na Ukrainie. Wszedł również (w 2003) w skład kolegium redakcyjnego czasopisma „Energetyka” publikowanego w Mińsku na Białorusi. W czasopiśmie Przykarczkiego Uniwersytetu w Iwanofrankowsku (Ukraina) „Fizika i chimija twerdogo tiła” powierzono mu w 2004r. funkcję zastępcy przewodniczącego kolegium redakcyjnego. Natomiast w czasopismach wydawanych przez Narodowy Uniwersytet „Lvivska Politiechnika”: Wisnik: Elementi Tieorij ta Priladi Tvierdotiloj Elektroniki oraz Wisnik: Elektronika, wszedł w skład komitetów redakcyjnych. Instytut Elektroniki i Technik Informacyjnych PL kierowany przez prof. W. Wójcika jest współorganizatorem wraz z partnerami ze wschodu szeregu konferencji, wśród których należy wymienić:

- Sztuczna inteligencja - systemy inteligentne II'2013,
- The Issues of Calculation Optimization (ISCOPT-XL),
- Intellectual systems of decision-making and problems of computational intelligence.
- Corocznych Interdisciplinary International PhD Workshops oraz krajowych Warsztatów Doktoranckich współorganizowanych z Instytutem Elektrotechniki w Warszawie oraz AGH.

Działania prof. W. Wójcika na rzecz integracji środowisk naukowych Polski i Ukrainy, a także Białorusi i Rosji zostały dostrzeżone, czego wyrazem było powierzenie mu funkcji wiceprezydenta Ukrainskiej Akademii Informatyki odpowiedzialnego za rozwój współpracy z krajami Unii Europejskiej.

Prof. W. Wójcik pełni również od 2007 roku funkcję rzeczywistego członka zagranicznego Ukrainskiej Akademii Informatyki, a także Członka Akademii Nauk Radioelektroniki Stosowanej Rosji, Ukrainy i Białorusi.

Ważnym obszarem działalności prof. W. Wójcika jest rozwój młodej kadry naukowej. Pełni on funkcję promotora zagranicznego w 6 otwartych przewodach doktorskich młodych pracowników naukowych z Kazachstanu, a jeden z przewodów został już zakończony. Dzięki jego zaangażowaniu i pomocy blisko 25 innych doktorantów realizuje swoje prace pod kierownictwem promotorów z Polski.

Z inicjatywy prof. W. Wójcika zostało powołane w Politechnice Lubelskiej biuro Programu Partnerstwa Wschodniego. Jego głównym celem jest aktywizacja współpracy uczelni z partnerami ze wschodu Europy. Wymiernymi efektami działalności są wspólne aplikacje Politechniki Lubelskiej i uczelni z Białorusi i Ukrainy o środki na realizację projektów. Takim projektem jest np. projekt „PL-NTU Transgraniczna wymiana doświadczeń”, realizowany w ramach Programu Współpracy Transgranicznej Polska - Białoruś - Ukraina 2007-2013 finansowanego ze środków Unii Europejskiej w ramach Europejskiego Instrumentu Sąsiedztwa i Partnerstwa. Realizacja projektu pozwoli na wymianę doświadczeń w zakresie organizacyjnym, dydaktycznym i naukowym pomiędzy Politechniką Lubelską a Łuckim Narodowym Uniwersytetem Technicznym (Ukraina). Kierowane przez prof. W. Wójcika biuro Programu Partnerstwa Wschodniego odpowiedzialne jest również za przygotowanie i realizację umów międzynarodowych, w tym

w zakresie tzw. programu podwójnego dyplomu. Dzięki osobistemu zaangażowaniu prof. W. Wójcika w tę działalność wielokrotnie zwiększała się liczba studentów ze Wschodu, którzy studiują na Politechnice Lubelskiej.

Współpraca lubelskiej uczelni technicznej i uczelni zagranicznych zwłaszcza z Ukrainą i Kazachstanu przejawia się również w zakresie tzw. mobilności akademickiej, w ramach której w 2013 roku blisko 30 doktorantów z Kazachstanu odbywało staże na Politechnice Lubelskiej, prawie 80 studentów studiów II stopnia przebywało na stażach krótkoterminowych, a ponad 10 studentów studiowało w ramach wymiany międzynarodowej. Program mobilności akademickiej to również wymiany pracowników naukowo-dydaktycznych, których w 2013 roku odnotowano blisko 10.

Zaangażowanie prof. Waldemara Wójcika we współpracę z uczeliami Ukrainy i Kazachstanu na różnych płaszczyznach spowodowało, że w 2011 roku otrzymał godność Doktora Honoris Causa Instytutu Cybernetyki im. W.M. Głuszkowa NAN Ukrainy (Kijów, Ukraina). Otrzymał również tytuły profesora honorowego Winnickiego Narodowego Uniwersytetu Technicznego (Winnica, Ukraina) w 2011 roku, Chersońskiego Narodowego Uniwersytetu Technicznego (Chersoń, Ukraina) w 2012 roku.

Prof. W. Wójcik jest autorem i współautorem ok. 400 prac naukowo-badawczych, w tym ponad 50 monografii i podręczników, ponad 40 prac z tzw. listy filadelfijskiej i ponad 60 publikacji z bazy SCOPUS.

Z swoją działalnością był wielokrotnie nagradzany nagrodami Rektora PL oraz PWSZ w Jarosławiu, nagrodami Ministra Nauki, Szkolnictwa Wyższego i Techniki (1979) oraz Ministra Edukacji Narodowej (1990), a także Srebrną honorową odznaką „Zasłużony dla Lublina” (1988), Medalem Komisji Edukacji Narodowej (2002), Brązowym Medalem „Za zasługi dla obronności kraju” (2007), jak również Srebrnym (1984) i Złotym Krzyżem Zasługi (1999), a w 2011 roku Krzyżem Kawalerskim Orderu Odrodzenia Polski.



Fot. 2. Uroczystość wręczenia prof. Waldemarowi Wójcikowi (z prawej) tytułu profesora honorowego Winnickiego Narodowego Uniwersytetu Technicznego (2011) z prawej: dr Krzysztof Świderek – Konsul Generalny RP w Winnicy, w środku: prof. Wołodymyr Grabko - Rektor



Fot. 3. Uroczyste posiedzenie rady naukowej Wschodniokazachstańskiego Państwowego Uniwersytetu Technicznego im. D. Serikbayeva poświęcone nadaniu tytułu profesora honorowego prof. Waldemarowi Wójcikowi

## COOPERATION HORIZONS AT DEPARTMENT OF AUTOMATION AND CONTROL, KazNTU

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**Abstract.** This article gives brief information about the history of the Kazakh National Technical University named after K.I. Satpayev (KazNTU) and the Department of Automation and Control (AaC). It describes the current state of educational, scientific and methodical work of the department. The article contains data on international cooperation and research activities of the department.

**Keywords:** Automation and Control, Kazakh National Technical University named after K.I. Satpayev

### HORYZONTY WSPÓŁPRACY KATEDRY AUTOMATYZACJI I STEROWANIA, KazNTU

**Streszczenie.** W artykule przedstawiono krótkie informacje o historii Kazachskiego Narodowego Uniwersytetu im. K.I. Satpaeva (KazNTU) i Katedry Automatyzacji i Sterowania. Przedstawiono aktualną działalność katedry w zakresie nauki, dydaktyki i metodyki. Omówiono współpracę międzynarodową i działalność badawczą katedry.

**Słowa kluczowe:** automatyzacja i sterowanie, Kazachski Narodowy Uniwersytet im. K.I. Satpayev

### 1. Brief information about KazNTU named after K.I. Satpayev

Kazakh National Technical University named after K.I. Satpayev is the oldest technical institution of higher education of the Republic Kazakhstan. Since its creation in 1934, it was called the Kazakh Mining and Metallurgical Institute, and since 1960 the Kazakh Polytechnic Institute. In 1994, it was converted to the Kazakh National Technical University (KazNTU). In 1999, for meritorious service in the preparation of engineering and technical staff of the country, KazNTU was named after the outstanding scientist, academician Kanysh Imantaevich Satpayev by the order of Government of the Republic of Kazakhstan.

During its existence, more than 100,000 professionals required for all sectors of the economy of the country were graduated from the university. Today, the university is ranked 1st in the ranking of universities in Kazakhstan on the academic performance of technical training schools. The university employs 165 doctors and 555 candidates of sciences, among them 42 academicians. The university is a member of the International and the European University Association, and is the parent institution of the SCO Network University in the following areas: nanotechnology, environment, information technology, and energy. The University provides training in 46 undergraduate specialties, 46 master programs and 22 doctoral programs.

### 2. A brief history of the Department of AaC

The department of Automation and Control is a leading educational and research unit of the University in the direction of automation and information for the economy sectors of the republic.

The beginnings of the creation of the department are traceable to sixties of the last century. In connection with the start of introduction of technologies and equipment having elements, systems of automation of processes and production into different industry sectors of the Republic (mining, metallurgical, energy etc.), a need for expertise in their design, development, introduction, and operation arised.

To meet this need, the specialties for education in areas of automation, electronics, electronics and computer technology were formed in the Kazakh polytechnic institution in 1962. In particular, the Department of Automation and telemechanics, and after some time the department of automation of metallurgical processes were organized. On the basis of these departments, the Department of Automation and Control was established in 2008.

Currently, the department trains bachelors, masters and doctoral candidates in the specialty of automation and control. The department has 28 highly qualified lecturers, including 3 doctors of science, 3 professors, and 9 candidates of science. The department is chaired by its graduate Doctor of Technical Sciences, Professor B. A. Suleymenov, who is a prominent

scientist and expert in the field of intelligent control systems. He is the author of over 150 scientific papers, among which 4 books, 4 textbooks. The four dissertations for the degree of Doctor PhD were defended under his leadership.

Since 70's, the Doctor of Technical Sciences, Professor, Honored Worker of Science and Technology of RK D. Zh. Syzdykov works, who over thirty years led the Department of automation and telemechanics, and is a well-known scholar in the field of the theory of identification and adaptive control. 15 PhD and 4 doctoral dissertations were defended directly under his supervision. Professor Syzdykov D.Zh. has published 170 scientific papers, including three monographs.

The graduate of the department, doctor of technical sciences, professor M.Sh.Baybatshaev, an eminent scientist in the field of robotization and automation of technological processes and production, is also working at the department. He is the author of more than 100 published scientific works including monographs and textbooks.

The candidates of technical sciences - professor Z. M. Yarmukhamedova, associate professors: S. K. Koshimbaev, B. K. Muhanov, A.H. Ibraev, A. A. Beisembayev, T. F. Omarov, O. I. Shiryaeva, M. M. Orynbet, N. S. Sarsembayev, S. K. Abdygaliev – have made a significant contribution to the establishment and development of the department.

In the last five years of its activities, the department is aimed at achieving the global goal of the university - the status of a research university of international level. To do this, the concrete measures on integration of vocational education and science with the production, orientation of the educational process on the current and future needs of the market and the national economy were taken.

### 3. The material and technical base of the department of AaC

In order to effectively prepare specialists in specialty "Automation and Control", the material- technical base of the department was radically transformed in the framework of a multi-stage system "Bachelor - Master - Doctor of Sciences". Now, the equipment and software products from the world's leading companies in the field of automation and control are used in the educational process: Siemens, Honeywell, Schneider Electric, Yokogawa, Festo, Fisher-Rosemount, OWEN, etc. It should be specially noted that the reconstruction of the material and technical base of the department was carried out for the expense of sponsorship at no cost to the university.

The research and training center for automation «KazNTU – Honeywell», in which students and undergraduates study programming, learn the skills of working with software products of U.S. aerospace company Honeywell, was created on the basis of the department. The equipment and software provided by Honeywell is worth more than 160,000 euros.

With the software and hardware automation means from the world-famous company Siemens, students familiarize themselves with the Kazakh-German Research and Training Center for Automation "KazNTU — Siemens".

The actual methods for automatic control of electro energetic processes and robotized complexes are studied in a specialized training center equipped by Schneider Electric with the assistance of the Ministry of Education of France. The center has three laboratories: "Automated Systems", "Research of Electric Power Systems", "Design and installation of electrical circuits". The Laboratory equipment is designed to teach the design, installation and commissioning of low-voltage power systems, for the demonstration of processes of the generation, transformation, and distribution of electric energy on real physical models.

Along with centers established jointly with foreign companies, two integrated laboratories operate at the department: computer modeling laboratory and software and hardware automation laboratory. The cooperation agreement between the KazNTU and Chevron allowed equipping the department laboratory with the training stand of the pneumatic automation for the Swiss company "Festo". The employees of the department are learning to work with laboratory stands for the Japanese company "Yokogawa". The negotiations on cooperation in the sphere of education and science with the leading Austrian IT - company "Bernecker + Rainer" are conducted.

The introduction of high level technology platforms into the educational process allows to learn modern methods and tools for automatic control of processes and industrial complexes on real physical models on the basis of the control computers.

The training of engineers can not be done without the students practice using modern equipment. The participation of students from the first years of learning in development of modern tools will facilitate the formation of a systematic approach to learn new knowledge and competencies in graduates.

#### **4. International cooperation and research activities of the Department of AaC**

The partnership of the department "Automation and Control" with foreign companies is mutually beneficial. The foreign companies operating in Kazakhstan through their participation in the development of training facilities of the department contribute to the training of graduates - the future purchasers of their equipment possessing skills to work on it and not requiring further retraining. At the same time, the department has significantly improved the substantive level and the quality of training of engineering and technical personnel in-demand in companies, which are the leaders of modernization.

Moreover, lectors, masters and doctoral students of the department improve their skills by learning to work the received equipment; some of them have been trained in Moscow training center "Siemens", Belgian educational center "Honeywell", training center "Festo", and Kazakhstan's leading innovative company "Sistemotekhnika".

Along with the implementation of educational functions, the advanced equipment of centers and laboratories is the basis for the conduction of researches. Over the past three years, the scientists of the department have performed or are in the stage of completion of the 12 research projects on request of enterprises and through grant funding from MES of RK.

On completed research projects, the technical projects are developed or systems of the automatic control of technological process for enterprises "Corporation "Kazakhmys", "Kaztransoil", "IntergazTsentralnayaAziya", "Kazphosphate".

The applied researches of the department is not only an opportunity to attract additional budgetary and extra-budgetary funds, but also an important necessary component of the qualitative educational process – performing of financed and initiative researches by students, undergraduates and doctoral students of the department. The results of many executed master's and doctoral dissertations are a good stepping stone for future innovative projects. Currently, we admit to a MA course up to

25 % of graduates of bachelor's program, and 5-6 best graduates of the MA course are annually admitted to doctorate at the department.

The active research activity of the department can improve the intellectual capacity of the department: now the steadiness of the teaching staff is 75%.

The republican scientific and production magazine "Vestnik avtomatizatsii", in which teachers, masters and doctoral students as well as the well-known scientists, engineers and business leaders of the country publish their works, is published at the department. The subscribers are large enterprises, promotional organizations, universities and libraries of Kazakhstan and CIS countries.

The department actively cooperates with renowned foreign universities and training centers: University of Florence (Italy), Slovak University of Technology, Lublin University of Technology (Poland), University named after J. Fourier (Grenoble, France), where teachers, doctoral and undergraduates undertake scientific internships. Professors of these universities are co-managers of doctoral department; foreign researchers are also involved in lecturing and cooperative research in Kazakhstan.

We would like to make a pointed reference to the active cooperation with the Lublin University of Technology. Professors of this university are scientific consultants of KazNTU, among them 16 are doctoral candidates of KazNTU, 12 are doctoral candidates of department AaC. The professor of this university Waldemar Voydzik has repeatedly came to lecture to master and doctoral candidates of the department, as well as for undergraduates and master candidates from other universities of Kazakhstan. As part of the cooperation agreement, the joint Kazakh- Polish monograph was published in 2012, and currently three volumes of articles of Polish, Ukrainian, and Kazakh scientists is prepared for publishing.

The results of targeted activities on improvement of work of the department allowed the specialty "Automation and Control" to get international accreditation in the accreditation agency ASIIN (Germany). Among the 16 departments training the specialists in this specialty, our every year takes the 1st place in the national ranking of educational programs.

Thus, the infrastructure of research activities created in the department will allow to successfully solving the problems of integration of education, science, and industrial production, and the orientation of the educational process to the needs of the development of innovative enterprises.

**Prof. Muhit Baybatshaev**

Doctor of Engineering Science, Professor of Automation and Control Department of Kazakh National Technical University after K.I. Satpayev, the famous scientist in the field of robotic automation of technology processes and manufacturing, the author of more than 100 scientific papers. For the long time was engaged in robotic automation problems of technology and non-ferrous metal industry of the Republic of Kazakhstan and Russia.



**Prof. Batyrbek Suleimenov**

Ph.D. Corresponding Member of the National Academy of Engineering. Head of Department of Automation and Control, Kazakh National Technical University (Almaty, Kazakhstan). The main scientific fields include the works in such spheres as: mathematical modeling of process facilities, optimization of controlled objects and synthesis of automated control systems.



**Ph.D. Ahanbay Beisenbayev**

Ph.D. in Engineering Science, Docent of Automation and Control Department of Kazakh National Technical University after K.I. Satpayev, the famous scientist in the field of robotic technology systems management, the author of more than 100 scientific papers. For the long time was engaged in robotic automation problems of technology and non-ferrous metal industry of the Republic of Kazakhstan and Russia.



# OPC TECHNOLOGY AS AN AUTOMATED SYSTEMS INTEGRATION TOOL

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**Abstract.** The paper features the application of the OPC technology in automated systems. It gives an insight into the considered technology and provides the prospects of the OPC technology development.

**Keywords:** OPC (OLE for Process Control), automated control system (ACS), component object model (COM), SCADA-system

## TECHNOLOGIA OPC JAKO NARZĘDZIE INTEGRACJI SYSTEMÓW ZAUTOMATYZOWANYCH

**Streszczenie.** W artykule rozpatrzeno możliwość zastosowania technologii OPC w systemach zautomatyzowanych. Dokonano przeglądu tej technologii, a także określono perspektywy jej rozwoju.

**Słowa kluczowe:** OPC, system sterowania automatycznego, Component Object Model (COM), system SCADA

### Introduction

Software for the modern process automation systems is becoming more complex and costly. The development of the software application sphere requires the use of more and more advanced tools and technologies. This is especially important in the development of complex software products that support different levels of Automated Control Systems (ACS).

A complex integrated system which covers automation at all business levels from the lowest control using sensors and actuating mechanisms to the level of company control mainly consisting of computing aids (personal computers, controllers, and other intelligent devices). Integration of automated system first of all means interaction between different software levels.

The ACS integration is aimed at real-time data exchange between different program systems developed using a variety of means that are installed on various platforms and operating on different computers. I.e. they should be aware how to request and send the required data to each other.

The technology was introduced by a consortium of world-famous hardware and software producers, such as the Rockwell Software, Fischer Rosemount along with Microsoft. OPC is a communication interface between different sources of data and software. This technology is based on the OLE/COM/DCOM architecture by Microsoft company [1].

### 1. Overview of OPC technology

OPC technology was developed to unify interaction of hardware and software mechanisms of Automated Control Systems. Within the frame of this technology the OPC-servers collect the data from controllers and transfer it to OPC-clients, for example SCADA-systems. Any OPC-client is able to exchange the data with any OPC-server independently of characteristics of equipment a definite OPC-server was developed for.

The main purpose of this technology is to provide software independence from definite hardware data sources for business dispatching systems developers.

The OPC-technology is meant to provide business software developers with a universal interface including a set of functions for data exchange between any appliances.

OPC was developed to ensure access of a client application to the lower level of a technological process in the most convenient form. Wide introduction of OPC technology in business has the following advantages:

- independence of applying dispatching systems from equipment used in a definite project;
- no need for modification of product software by its developers after equipment modification or manufacturing of new products;
- customer freedom to choose between equipment suppliers, as well as the possibility of integrating this equipment in the enter-

prise information system that covers the whole system of production control and logistics.

The basic idea of OPC-technology is that client software applications could receive data from the definite number of different sources, for example PLC, intelligent field equipment, data base management systems, other software, i.e. OPC is applied not only to data exchange with other hardware, but also to connection of one application to another [2].

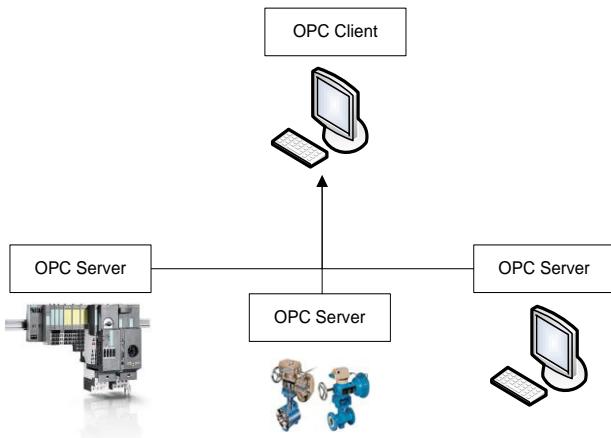


Fig. 1. Operation principle of Client – Server architecture

OPC technology is based on the Microsoft Distributed Component Object Model (DCOM), and sets requirements for the classes of data access objects and their specialized interfaces for use by developers of client and server applications. OPC technology as a means of interacting with a technical device can also be used to develop customized programs using C++, Visual Basic, VBA, or Delphi. The use of OPC in the development of customized software allows hiding from a developer the complexity of communication with the hardware, thus presenting a simple and convenient way to access the hardware via the COM object interfaces [5].

There are three main ways of obtaining data from an OPC server by an OPC client: synchronous reading, asynchronous reading and subscription. At synchronous reading a client sends a request to the server with a list of variables of interest to him and waits for the server to execute it. At asynchronous reading a client sends a request to the server and continues working. When the server has fulfilled the request the client is notified. In the case of subscription a client sends to the server a list of the variables of interest, and the server then sends to the client the information of the changed variables from his list on a regular basis. According to the OPC terminology these lists are called groups. Each client can simultaneously support many groups with different rates of updating.

The basic unit of data in OPC is a variable. A variable can be of any type allowed in OLE: various integer and real types, boolean, string type, date, currency, variant type, etc. Besides, a variable can be an array.

There is a fairly long list of OPC standards presented in Table 1. The OPC Foundation Consortium tries to cover all aspects of interaction with manufacturing equipment. Leading manufacturers of equipment and automation systems take part in the development of specifications; they try to take into account their own experience and provide someone who will use the OPC with absolutely everything he needs.

OPC specification describes two sets of interfaces:

- OPC COM Custom Interface;
- OPC OLE Automation Interface.

COM OPC Custom Interface group of standards describes the interfaces and procedures of OPC components and objects. This group of standards is designed primarily for high-level language software developers [5].

OPC OLE Automation Interface group is designed for software developers

Table 1. List of OPC standards

Name of standard	Designation
OPC Common Definitions and Interfaces	Common to all OPC Specification Interfaces
Data Access Custom Interface Standard	COM interface specification for operational data exchange
Data Access Automation Interface Standard	COM interface specification for operational data exchange, programming in Visual Basic languages
OPC Batch Custom Interface Specification	COM interface specification for hardware configuration
OPC Batch Automation Interface Specification	COM interface specification for hardware configuring, programming in Visual Basic languages
OPC Alarms and Events Custom Interface Specification	COM interface specification for event and alarm handling
OPC Alarm and Events Automation Interface Specification	COM interface specification for handling events and alarms, programming in Visual Basic languages
Historical Data Access Custom Interface Standard	COM interface specification for data storage
Historical Data Access Automation Interface Standard	COM interface specification for data storage, programming in Visual Basic languages
OPC Security Custom Interface	COM interface specification for processing data access rights

The applications that implement the abovementioned standards are called OPC servers. It is the OPC server that is responsible for receiving data from equipment, its processing and storage. The applications connected to OPC servers with the aim of receiving data from them are called OPC clients. An OPC client may connect to OPC servers supplied by one or several manufacturers. As follows from Table 1 the standards developed by OPC Foundation cover almost all the aspects of developing technological process automation control systems. In practice software developers implement only some of these specifications. The most popular are Data Access standard realizations [6].

## 2. Integration of OPC technology in automation systems

Figure 2 presents the diagram illustrating possible areas of OPC-server use in an enterprise automation system. There are several control levels:

- lower level – field buses and separate controllers;
- middle level – shop networks;
- technological process ACS level – SCADA type systems operation level;
- production ACS level – level of enterprise resources control applications.

Each of these levels could be serviced by an OPC-server supplying data to an OPC-client at a higher level.

An OPC DA server is the most widely used server in industrial automation. It provides data exchange, recording and reading between a client program and physical devices. The data consists of three fields: value, quality and timestamp. The data quality parameter allows communicating the information about the measured value exceeding the dynamic range, the lack of data, communication failure, etc. from a device to client software [3].

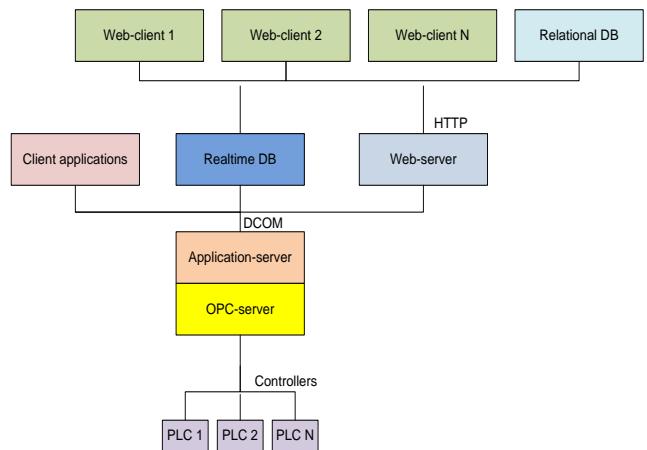


Fig. 2. Possible range of use of OPC-servers in enterprise automation systems

There are two standard modes of reading data from an OPC-server:

- synchronous mode: a client sends a request to a server and waits for reply;
- asynchronous mode: a client sends a request and switches to other tasks. After processing the request the server sends notification to the client, and the client receives the provided data.

In each of these modes data can be read either from the OPC-server cash, or directly from a physical device. Reading from cash is much faster, but the data can become outdated by the moment of reading. Thus a server should regularly update the data at the maximum allowed frequency. To reduce the processor load a frequency update parameter is used, so frequency may be set individually for each group of tags. Besides some tags may be made passive, then their values will not be updated by the data from a physical device [3, 7].

Recording data into a physical device can be performed by only two methods: synchronous or asynchronous; and it is recorded directly into a device without intermediate buffering. In the synchronous mode the recording function is active until a physical device provides confirmation of the record completion. This process could take a good deal of time during which a client is waiting for the completion of function and is not able to continue working. In the asynchronous record mode a client sends data to a server and goes on working. Upon completion of recording the server will send a corresponding notification to the client.

An OPC DA server may have a user interface which allows executing any auxiliary functions that simplify operating equipment. For example besides data exchange with SCADA an OPC server allows performing the following useful functions [7]:

- search of equipment connected to an industrial network;
- setting equipment parameters (designation, address, data exchange speed, watchdog timer period, control checksum availability, etc.);
- creating a hierarchical representation of tag names;
- observation of tag values;
- control of OPC server access rights.

In accordance with the standard an OPC server is automatically registered in the Windows register during installation.

The server is run similar to any other program or automatically from a client program.

In perspective open SCADA-programs an OPC interface could be included either as one of the interfaces for interaction with

external programs, or as a basis structure of a SCADA-program. Tools for developing OPC-components could be supplied either by SCADA program developers or by independent software manufacturers. Using special software tools for development of OPC-servers and OPC-clients significantly simplifies the development of OPC-components, as it proposes ready OPC-interface implementation.

Examples of systems architecture including OPC-servers and OPC-clients are provided in Figure 3 and 4. A program in C++

language, for example SCADA-system, or a program in Visual Basic, VBA, or Delphi languages supporting the implementation of COM-objects (Figure 3) could be used as an OPC-client. A program in C++ language interacts with an OPC-server an OPC Custom interface, and a program in Visual Basic, VBA, Delphi languages – through an OPC Automation interface. OPC-servers and OPC-clients can work only on computers and controllers with operational systems supporting DCOM technology (for example, Windows XP and Windows CE) [1, 7].

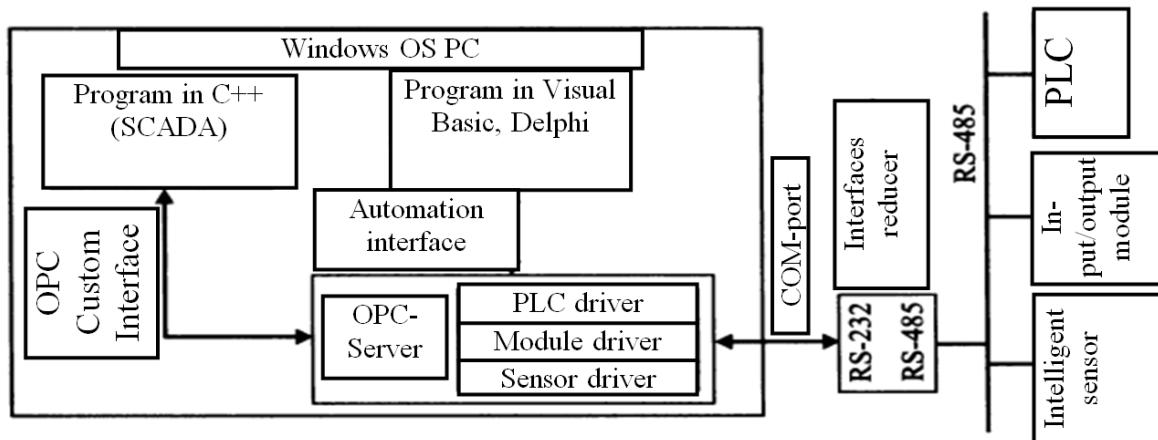


Fig. 3. Example of interaction of applications and physical devices through an OPC-server on one computer

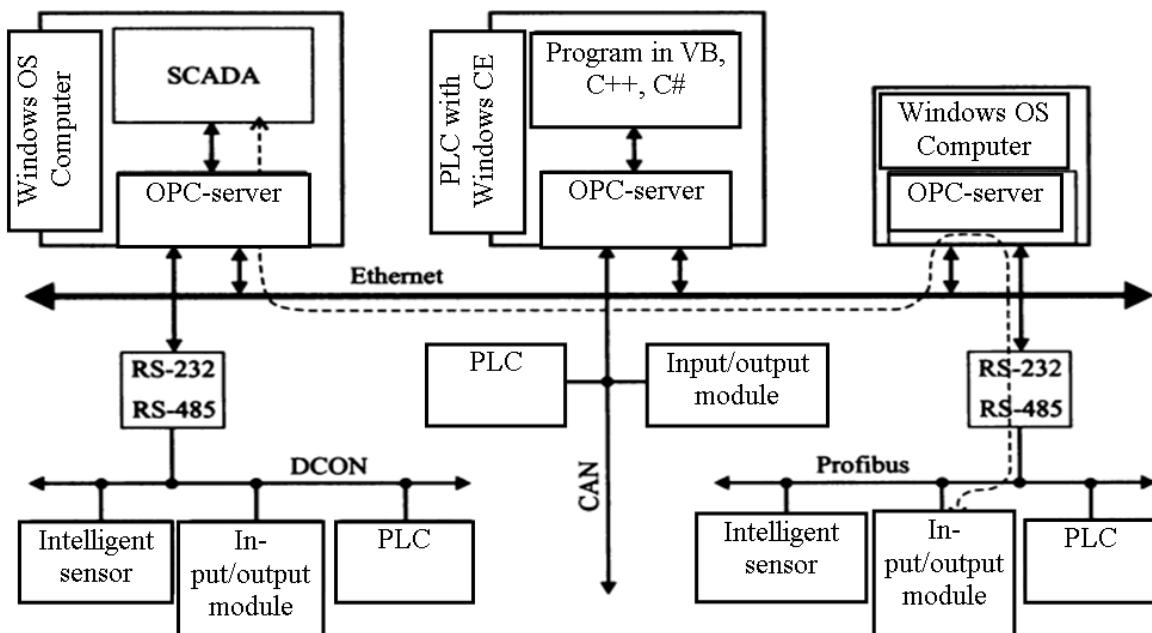


Fig. 4. Example of applying OPC-technology for network access to data in automation systems

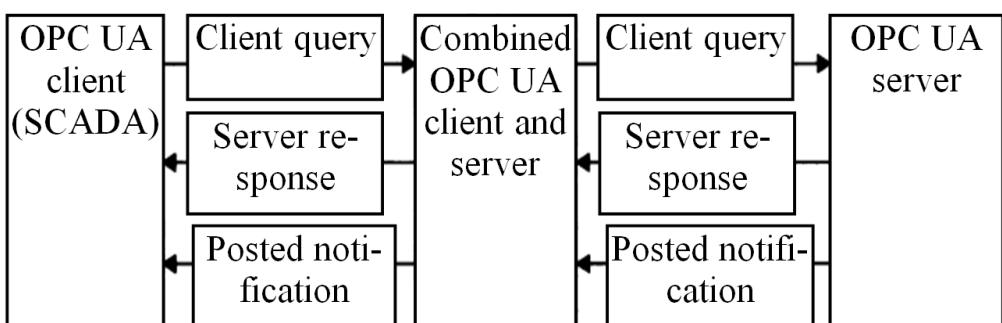


Fig. 5. Example of communication of OPC UA-clients and servers in one application

OPC-server connects to physical devices in many ways that are not provided in the standard. A client program and an OPC-server could be installed on the same computer (Figure 3) or on different computers of the Ethernet (Figure 4). In case there are several computers, each of them can have an OPC-server and physical devices connected to it.

In such a system any OPC-client from any computer is able to communicate with any OPC-server, including those installed in other computers of the network. This could be achieved due to DCOM technology which uses a remote procedure call (RPC). For example, a SCADA-system (Figure 4) may request the input/output module data via the path shown by a dashed line. It should be taken into consideration that computers and controllers in such architecture are able to operate with different industrial networks [1, 7].

Except the OPC DA technology there is a more advanced standard specification for data exchange in industrial automation systems which is called "OPC Unified Architecture". It is considered a new generation of the OPC technology. The OPC UA sets message exchange methods between an OPC server and a client which do not depend on a hardware/software platform, as well as on the type of interacting networks and systems. A system based on the OPC UA may contain a lot of clients and servers. Each client can work with several servers simultaneously. Each server can serve several clients. User applications, for example a SCADA-system could create combined client and server groups for retranslating messages they are exchanging with other clients and servers as shown in Figure 5. An application software program, for example a SCADA system [3, 4] becomes a client during interaction with an OPC server.

### 3. Conclusion

As of today OPC is a perspective technology for integration of hardware and software in automation systems. The OPC proposes standards for exchange of process data with substantial opportunities. But there is still a lot of equipment and software which are not covered by OPC-technologies. However, Microsoft Corporation does not provide COM/DCOM anymore, these technologies have been replaced by more advanced, for example .NET. Yet only OPC DA standard is widely used. Nowadays a lot of manufacturers equip their products with OPC DA servers. The OPC HDA standard has been effectively developed recently, still other specifications have not made such progress. The more advanced OPC UA technology is a promising direction.

OPC technology is a powerful and unified tool. It has made substantial contribution to standardization of embedded systems interacting with computers. A lot of modern developers successfully apply it in the development of technical systems.

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# DEVELOPMENT OF SIMULATION MODEL OF STRIP PULL SELF-REGULATION SYSTEM IN DYNAMIC MODES IN A CONTINUOUS HOT GALVANIZING LINE

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**Abstract.** The paper deals with the peculiarities of development of simulation model of strip pull self-regulation system in a continuous hot galvanizing line. The results of simulation modelling are provided.

**Keywords:** continuous hot galvanizing line, control system, dynamic mode

## EWOLUCJA MODELU SYMULACYJNEGO SYSTEMU SAMOREGULACJI NAPRĘŻENIA TAŚMY W TRYBIE DYNAMICZNYM W LINII CIĄGŁEGO CYNKOWANIA NA GORĄCO

**Streszczenie.** W artykule rozpatrzone cechy szczególne konstruowania modelu symulacyjnego systemu regulacji naprężenia taśmy w linii ciągłej cynkowania na gorąco. Przedstawiono wyniki badań symulacyjnych.

**Slowa kluczowe:** linia do ciągłej galwanizacji na gorąco, system sterowania, tryb dynamiczny

## Introduction

A continuous hot galvanizing line (CHGL) is a complex electromechanical system, the functioning reliability and quality of which depends on physical and mechanical properties of the treated metal strip and work modes of a multimotor drive interrelated through the strip.

When the line head end is stopped for the metal strip coil change and welding of the strip ends, the unit's middle technological part continues movement at the operating speed as the strip is being pulled from the vertical looper. At this time the dynamic processes leading to longitudinal vibrations in the treated strip occur. As a result, the so-called "ruffles" are formed in the treated strip during treatment in the thermochemical treatment (TCT) furnace under the effect of high temperature that leads to rejection of the material.

## 1. Development of simulation model

On CHGL there were held experiments on definition of dynamic properties of the treated metal strip [9].

For strip pull stabilization in the furnace during the stopping of the line head end it is offered mounting of a roller working in the torque mode before the TCT furnace. A lower roller of the Pulling Station 2 (the active roller) will be used for this purpose. During the movement of the looper car the roller will make progressive motion against the strip movement, thereby creating additional pull in the strip. The error ratio of the effective and preset pulls will be applied to the motor shaft of this roller as a static resistance moment.

The resistance moments of the Pulling Station 2 motor actuators are described by the equations [2]:

$$\left. \begin{aligned} M_{c5} &= \left( F_{5,6} + F_{fr} \right) \frac{r_5}{i_5} + \frac{a \cdot n_5}{60} + K_{red} F_4 \\ M_{c6} &= \left( -F_{5,6} + F_{fr} \right) \frac{r_6}{i_6} + \frac{a \cdot n_6}{60} + K_{red} F_7 \end{aligned} \right\} \quad (1)$$

where  $M_{c5}$ ,  $M_{c6}$  are upper and lower rollers' resistance moments, Nm;  $F_{5,6}$  is the pulling capacity in the strip, N;  $F_{fr}$  is the friction force, N;  $r_5$  and  $r_6$  are the upper and lower rollers' radii;  $i_5$  and  $i_6$  are the upper and lower rollers' gear reduction rates;  $a$  is the dissipation factor which characterizes natural vibrations damping process in the system, N·m·s;  $n_5$  and  $n_6$  are the upper and lower roller motors' speed of rotation, r/min;  $K_{red}$  is the reduction factor that takes into consideration the reduction of the neighbouring interrelating masses to one shaft;  $F_4$ ,  $F_7$  are the pulling capacities in the strip in the looper and in the work site of the TCT furnace relatively, Nm.

The force which the active roller will act with on the treated strip is defined from the equation [6]:

$$F_p = \frac{mdv}{dt}, \quad (2)$$

where  $m$  is the active roller mass, kg;  $v$  is the active roller linear speed;  $d/dt$  is the differentiation operator.

A static moment given by the strip to the pinch station 2 rollers during the movement of the active roller is defined by the formula [4]:

$$M_{add} = \frac{r}{i} F_p, \quad (3)$$

where  $r$  is the radius of the active roller block;  $i$  is gear reduction rate.

Based on the progressive motion of the active roller the equations (1) will take on the form [10]:

$$\left. \begin{aligned} M_{c5} &= \left( F_{5,6} + F_{fr} \right) \frac{r_5}{i_5} + \frac{a \cdot n_5}{60} + M_{add} + K_{red} F_4 \\ M_{c6} &= \left( -F_{5,6} + F_{fr} \right) \frac{r_6}{i_6} + \frac{a \cdot n_6}{60} - M_{add} + K_{red} F_7 \end{aligned} \right\} \quad (4)$$

where  $M_{add}$  is the moment transferred to the strip by the active roller's progressive motion.

The static moment transferred by the strip will influence the motor shaft of the lower roll of the TCT furnace at the active roller's progressive motion [1].

The equation of the resistance moment of the lower roller of the furnace treatment site will be as follows [5]:

$$M_{c8} = \left( -F_{7,8} + F_{fr} \right) \frac{r_8}{i_8} + \frac{a \cdot n_8}{60} + K_{red} F_6 + M_{add} \quad (5)$$

where  $F_{7,8}$  is pull capacity taking place between the two interrelating masses of the TCT furnace rollers, N;  $F_{fr}$  is the friction force, N;  $r_{7,8}$  is the lower roller (reduction) radius, m;  $i_8$  is the gear reduction rate;  $a$  is the dissipation factor that characterizes natural vibrations damping process in the system N·m·s;  $n_8$  is the lower roller's speed of rotation, r/min;  $K_{red}$  is the reduction factor that takes into consideration the reduction of the neighbouring interrelating masses to one shaft;  $F_6$  is the pulling capacity in the strip in the Pulling Station 2;  $M_{add}$  is the static resistance moment transferred by the strip at the active roller's progressive moment.

The structural flowcharts of mathematical models of the Pulling Station 2 and the TCT furnace treatment site with consideration of introduction of the active roller's influence are given in Figures 1, 2 [3].

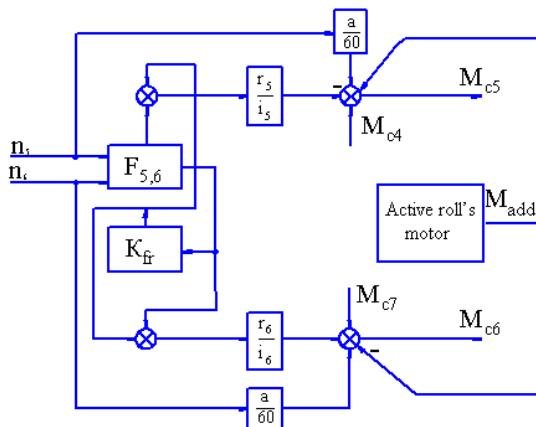


Fig. 1. The structural flowchart of the Pulling Station 2 motor actuator mathematical model

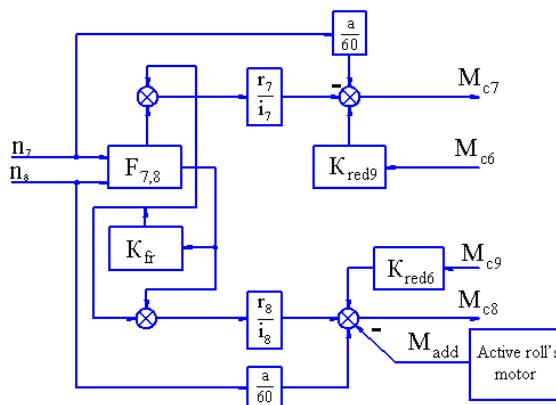


Fig. 2. The structural flowchart of the TCT furnace treatment site mathematical model

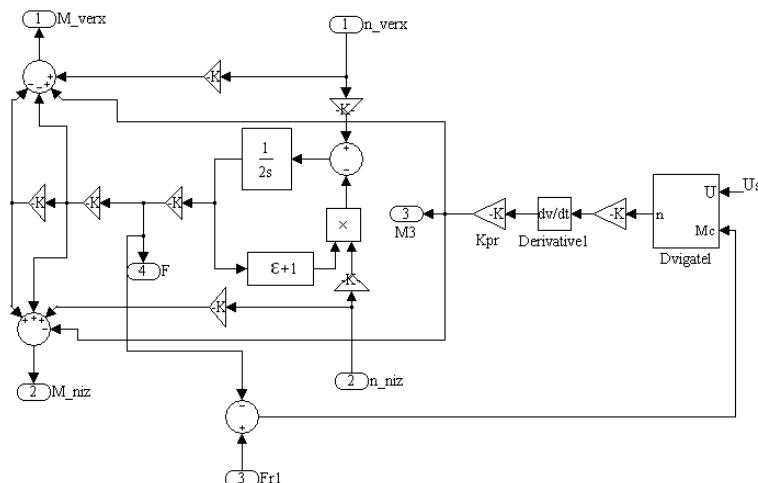


Fig. 3. The simulation model of the Pulling Station 2 motor actuator

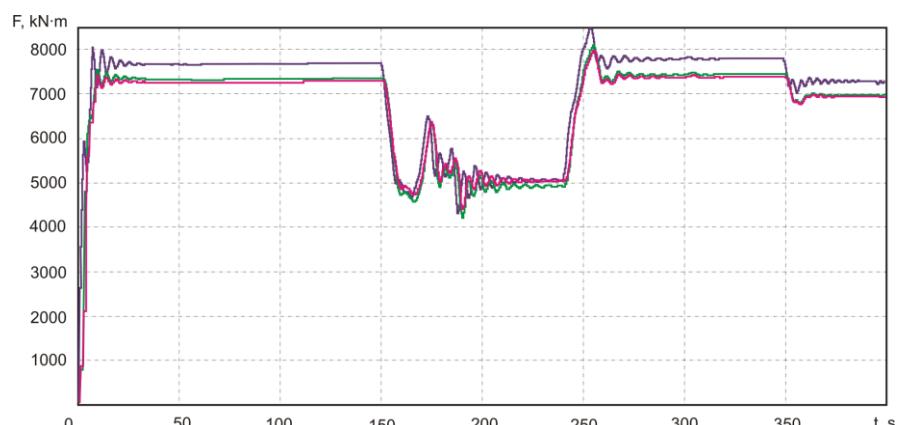


Fig. 4. The oscillograms of pulling capacities in the strip before the introduction of the active roller's action

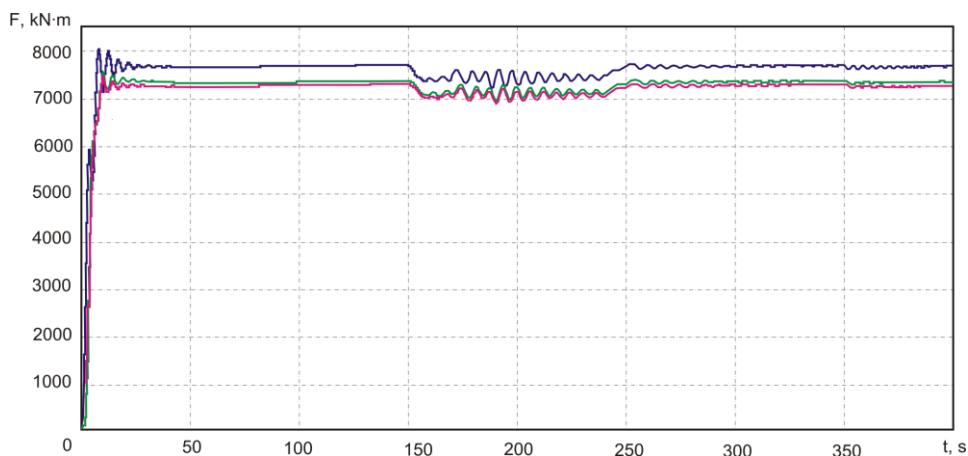


Fig. 5. The oscillograms of pulling capacities in the strip after the introduction of the active roller's action

By the received structural flowcharts in the Simulating package of the MATLAB 7 system there were built simulation models of the mechanisms of CHGL motor actuators with consideration of the active roller motion [8]. The simulation model of the Pulling Station 2 motor actuator is given in Figure 3.

The input values in the model are: the voltage supplied to the stator winding of the active roller's motor; the rotation frequencies of the motors of the Pulling Station 2 upper and lower rollers; the static resistance moment applied to the active roller's motor shaft formed by difference of signals of the effective  $F$  and preset  $F_{rl}$  pulls. The output values are the resistance moments of the Pulling Station 2 upper and lower rollers. The active roller's motor is represented by the "Dvigatel" subsystem [7].

The oscillograms of the pulling capacities in the strip in the TCT furnace before the introduction of the active roller action and after it are given in Figures 4, 5.

The oscillograms display (from top to bottom relatively) the signals of the pull capacities of the Pulling Station 2 at the strip treatment site in the TCT furnace and at the site of the furnace with pullers.

## 2. Results

The analysis of the oscillograms shows that after introduction of the active roller's action the amplitude of pull capacities vibrations reduced by 85%. The amplitude of the low-frequency component of pulling capacity vibrations in the strip makes up 0,3 kN, that is a norm. There is observed an increase of the low-frequency component in the end of the process of pulling the strip from the looper by 45%. It is connected with the increase of the strip pull in the looper in connection with the reduction of its length. As the high-frequency component does not take part in the process of folding, so we neglect its amplitude change.

## 3. Conclusion

Therefore, the developed mathematical and simulation models adequately reflect the processes in the treated strip in dynamic modes.

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## OPTIMAL CONTROL SYSTEM OF DIESEL AUTOMOTIVE ENGINEERING BY EXAMPLE OF OPEN PIT MOTOR TRANSPORT

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**Abstract.** The paper investigates the optimal control system of diesel automotive engineering with application of complex criteria, depending on fuel consumption rate and travel time, with adjustable coefficients of physical process mathematical model, considering influence of disturbing effects factors. This control principle allows saving fuel consumption rate, reducing transport influence on environment, and also reducing the importance of human factor for motor transport control.

**Keywords:** optimal control, fuel consumption, quarry road transport, pit road transport, mobile resource management, vehicle control

### SYSTEM AUTOMATYCZNEGO ZARZĄDZANIA ZESPOŁEM SAMOCHODÓW Z SILNIKAMI DIESLA NA PRZYKŁADZIE TRANSPORTU SAMOCHODOWEGO W KAMIENIOŁOMACH

**Streszczenie.** W artykule zostało rozpatrzone optymalne sterowanie procesem przemieszczania pojazdów z zastosowaniem złożonego kryterium, zależnego od zużycia paliwa i czasu przejazdu, ze zmiennymi współczynnikami modelu matematycznego fizycznego procesu, uwzględniając wpływ czynników zakłócających. Otrzymany system sterowania pozwala na oszczędne zużycie paliwa, zmniejszenie wpływu transportu na środowisko i obniżenie wpływ czynnika ludzkiego na zarządzanie transportem samochodowym.

**Słowa kluczowe:** sterowanie optymalne, zużycie paliwa, transport samochodowy w kamieniołomach, zarządzanie transportem samochodowym, ocena stanu technicznego

### Introduction

Transport Strategy of Republic of Kazakhstan (hereinafter – the Strategy) approved in Kazakhstan up to 2015 [1] has a federal value and was stated in "Kazakhstan at the threshold of the new breakthrough in its development", the Message of the President of the Republic of Kazakhstan to the People of Kazakhstan dated March 1, 2006. The Strategy was developed by the Ministry of Transport and Communication of the Republic of Kazakhstan. The target of the Strategy is "Faster growth of transport and communication complex able to fully satisfy requirements of economy and population in transportation services". The basic strategic missions and principles are as follows:

- achievement of highest efficiency of transportation processes and reduction of transport component share in finished goods price for internal, transit, and export-import communication;
- competitive recovery of Kazakhstan transportation system at the cost of innovative technologies and clustered development of infrastructure;
- providing safety for transportation processes, reducing the number and severity of transport accidents; providing ecological safety and rational utilization of energy resources.

### 1. Background literature overview

An automobile is one of the most popular means of transport in the structure of the transportation cycle used at development of deposits [9, 11]. Development of mining operations and increasing of open pit depths leads to increasing of mine rock transportation amount, which at the same time causes the deterioration of road conditions and affects the cost-performance indicators of rock mass transportation [1]. Besides that, the ecological situation due to exploitation of diesel trucks accompanied by emissions of toxic substances into the atmosphere also takes a turn for the worse [13].

Analysis of data processing results [6] with regard to reliability of open pit motor transport at the enterprises of mining industry shows that about 32% of all failures are accounted for the engine and its systems. The main causes are both increasing of automobile run and corresponding deteriorated technical conditions (ageing, wearing of friction parts, etc.), and also deficiencies in operation of maintenance team supporting its working efficiency.

Besides different emergencies often occur during mining operations [14], they could be conditionally split into four basic groups: poor technical mine and road conditions, violation of traffic rules, inefficient organization of motor transport performance, technical failures of dump trucks. In addition, as statistics analysis shows [14], about 20% of drivers causing accidents, were the 1<sup>st</sup> category drivers, more than one third were the 2<sup>nd</sup> category drivers, and almost 50% were the 3<sup>rd</sup> category drivers. This clearly points to the need to improve skills of drivers. A lot of accidents also occur at the night shift, which is related to higher stress of drivers and influences their working efficiency due to over-fatigue. After increasing the capacity and sizes of open pit motor transport, and also complication of transport communication the matter of accident free traffic became one of top priorities.

Besides, it is also required to provide not only safe traffic of the motor transport, but also its optimal operating mode with regard to fuel consumption and travelling speed [5, 14]. Optimal control of motor transport traffic should be provided by the driver, but it is not always possible due to human factors, such as qualifications, fatigue, inattention etc.

### 2. Goal and problem setting

The aim of this research is based on the performed analysis, the aims and objectives of the Strategy. The research is targeted at improvement of open pit motor transport working efficiency in the process of its exploitation. The overall goal of work is the reduction of human factor influence on trucks driving in the process of their exploitation in the mining sphere. The set goal can be achieved by solution of the following problem: development of mathematical model and optimal control system for diesel automotive engineering in the process of exploitation.

### 3. The procedure

Developed system realizes optimal control with an application of improved physical process model. It consists of three levels: I – upper, II – middle, and III – lower (Figure 1). The upper level keeps truck parameters and traffic route information. The middle level performs search of optimal crank shaft rotations (CS), fuel injection advance angle (FIAA) and gear in accordance with preset efficiency criteria. The lower level performs automated control of fuel rack supporting minimum rotations at each section of a traffic route.

Let us examine the control system structure in details.

Upper Level I consists of the following structural blocks:

- Block 1 has the following preset parameters for each type of truck: minimum rotation speed of CS  $n_{e \min}$  and maximum rotation speed of CS  $n_{e \max}$ ; weight of truck  $G_a$ ; transmission efficiency factor  $\eta_{TP}$ ;  $k$  – air resistance coefficient;  $F$  – truck front surface;  $r_k$  – driving wheel radius;  $i_k$  – drive ratio of gearbox (GB) etc.;
- Block 11 keeps the mathematical model of truck and engine;
- Block 12 performs specification of model parameters based on measuring results;
- Block 13 implements the target function of optimal control;
- Block 14 keeps the route memory, including minimum  $\vartheta_{a \min}$

and maximum  $\vartheta_{a \max}$  travel speed at different sections of traffic routes. The speed limit is set in accordance with traffic safety according to the traffic rules and road conditions. Besides there is a road resistance coefficient  $\psi$  for each section of route in this block. A skilled driver (expert) can correct travel speed without exceeding the preset range. In such case corrections in the block 14 are required.

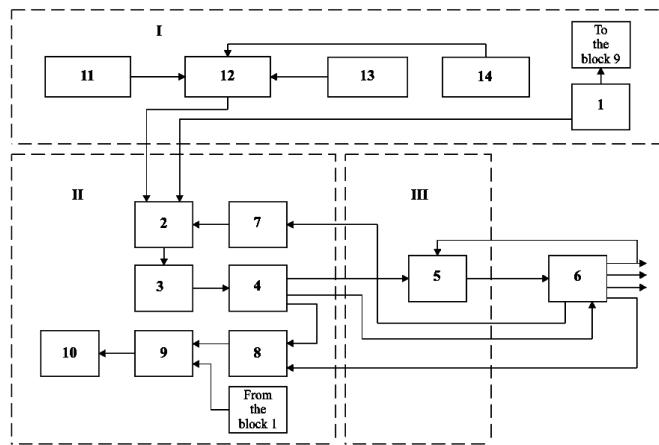


Fig. 1. Block scheme of an optimal control system

Middle Level II consists of the following structural blocks:

- in Block 2 adjustment of optimal control equations coefficients is performed;
- Block 3 is designed for numerical solution of optimal control equations;
- in Block 4 the calculated optimal variables are transferred;
- in Block 7 adjusted model coefficients are recorded;
- in Block 8 calculation of deviations of optimal values from current measured value is performed;
- in Block 9 comparison of calculated deviation in the block 8 with preset maximum deviation along with the calculation of percentage is performed, which is the validation of fuel equipment (FE) technical conditions;
- in Block 10 conclusions on the validation of FE technical conditions as per one parameter are made.

Lower Level III consists of structural Block 5 – control block regulating magnitudes of variables at the outlet of a control object (Block 6) calculated in Block 4.

To perform computer modeling a control object's mathematical model is used as a control object (block 6). After the system is introduced in site, its mathematical model is replaced by a real truck.

A mathematical model of a control object represents both a model of a diesel combustion engine (CE) and a truck model as a whole.

The mathematical model of a diesel engine in the form of a control object regarding rotation speed of CS  $n_e$  from rack shift  $h$  and load  $N$  (and also from resistant moment coefficients  $K_{d2}$  and drive torque  $K_{d1}$ ) is given in the following equation [5, 7]:

$$n_e = \frac{K_{d1} \cdot h - K_{d2} \cdot N}{T_d \cdot p + 1} \quad (1)$$

Dependence of the truck travel speed from CS rotation speed and drive ratio of GB [2]:

$$\vartheta_a = 0,377 \cdot \frac{r_k \cdot n_e}{i_k \cdot i_0} \quad (2)$$

where  $r_k$  – driving wheel radius;  $n_e$  – CS rotation speed;  $i_k$  – drive ratio of GB;  $i_o$  – drive ratio of main gear; 0,377 – speed conversion factor in km/h.

The mathematical model of truck fuel consumption could be determined basing on the following equation [4]:

$$Q_p = \frac{g_e \cdot (G_a \cdot \psi + 0,077 \cdot k \cdot F \cdot \vartheta_a^2)}{0,36 \cdot 10^5 \cdot \eta_{TP} \cdot \rho_T} \quad (3)$$

where  $g_e$  – specific fuel consumption;  $G_a$  – estimated truck weight;  $\psi$  – road resistance coefficient;  $k$  – air resistance coefficient;  $F$  – truck front surface;  $\vartheta_a$  – truck speed;  $\eta_{mp}$  – transmission performance coefficient;  $\rho_T$  – fuel density;

Equation (3) is approximate, because the following variables were not considered: rack moving, drive ratio of GB and main gear, wheel radius and engine load. To eliminate these violations, using (1) and (2) on the basis of (3), and as a result of corresponding re-expressions we obtain an improved mathematical model of fuel consumption rate considering above mentioned variables:

$$Q_p = \frac{g_e \cdot \left( G_a \cdot \psi \cdot i_k^2 \cdot i_0^2 + 0,011 \cdot k \cdot F \cdot r_k^2 \cdot \left( \frac{K_{d1} \cdot h - K_{d2} \cdot N}{T_d \cdot p + 1} \right)^2 \right)}{0,36 \cdot 10^5 \cdot \eta_{TP} \cdot \rho \cdot i_k^2 \cdot i_0^2} \quad (4)$$

where  $Q_p$  – fuel consumption;  $r_k$  – driving wheel radius;  $i_k$  – drive ratio of GB;  $i_o$  – drive ratio of main gear;  $N$  – engine load;  $h$  – rack moving;  $g_e$  – specific fuel consumption;  $G_a$  – truck designed weight;  $\psi$  – road resistance coefficient;  $k$  – air resistance coefficient;  $F$  – truck front surface;  $\eta_{TP}$  – transmission performance coefficient;  $\rho$  – fuel density.

Based on (1, 2, 4) the simulation modeling of dependences of fuel consumption ( $Q_p$ ), CS rotation speed ( $n_e$ ), and truck travel speed ( $\vartheta_a$ ) on the time in the case of fixed fuel rack and gear were performed. The results are given in Figure 2.

Development of an optimal control system.

The optimal control system includes a mathematical model of a control object physical process, the selection of a target function and limitation for control and controlled variables.

We develop a mathematical model of a diesel engine and truck fuel consumption in the process of their exploitation.

The fuel consumption could be determined by the following formula [10]:

$$Q_p = \frac{g_e \cdot N_e}{10000 \cdot \vartheta_a \cdot \rho} \quad (5)$$

where  $g_e$  – specific fuel consumption kg/(h.p.h);  $N_e$  – applied engine effective power;  $\vartheta_a$  – travel speed;  $\rho$  – fuel density.

Engine brake power is determined by the formula [4]:

$$N_e = G_a \cdot \psi \cdot \vartheta_a + 0,077 \cdot k \cdot F \cdot \vartheta_a^3 \quad (6)$$

where:  $G_a$  – truck weight;  
 $\psi$  – total road resistance [3];  
 $k \cdot F$  – truck wind shape factor [4].

Considering transmission performance coefficient the formula (6) will take the following form:

$$N_e = \frac{G_a \cdot \psi \cdot V_a + 0,077 \cdot k \cdot F \cdot \vartheta_a^3}{\eta_{TP}} \quad (7)$$

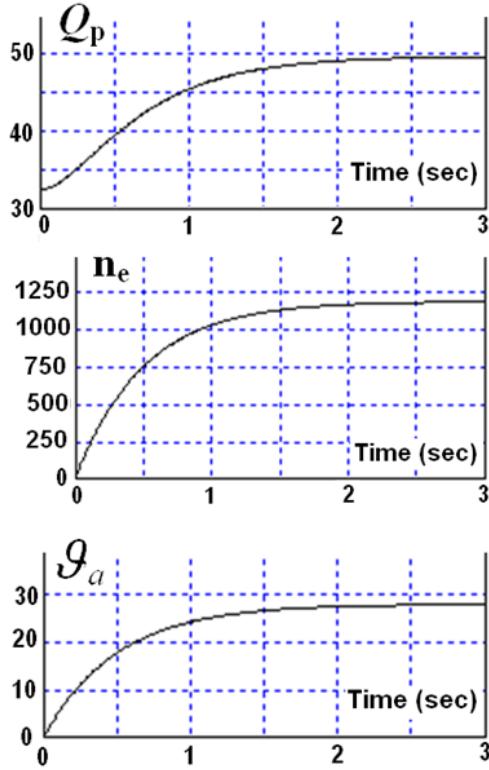


Fig. 2. Modeling results

If an engine is operating in conditions of variation of FIAA values and CS rotation speed, the fuel specific consumption changes, which can be seen on the full-load curve [3, 4, 5, 10, 12]. The dependence of fuel specific consumption is usually represented either for different CS rotation speed, or for different FIAA and definite CS rotation speed. Approximating the values by complete quadric polynomial with the help of Curve Expert Pro software, we can make a diagram (Figure 3) of the interpolation dependence of fuel specific consumption on CS rotation speed and FIAA. It allows calculating specific consumption against any of their values:

$$g_e = a + b \cdot n_e + c \cdot \varphi + d \cdot n_e^2 + e \cdot \varphi^2 + f \cdot n_e \cdot \varphi \quad (8)$$

where  $a, b, c, d, e, f$  are coefficients whose values depend on the engine type;  $\varphi$  – FIAA;  $n_e$  – CS rotation speed.

Based on dependence of truck fuel consumption (5), effective power (7), truck travel speed (2), and also dependence of fuel specific consumption (8) we obtained the mathematical model of fuel consumption:

$$Q_p = \frac{G_a \cdot \psi}{10000 \cdot \eta_{mp} \cdot \rho} (a + b \cdot n_e + c \cdot \varphi + d \cdot n_e^2 + e \cdot \varphi^2 + f \cdot n_e \cdot \varphi) + \frac{0.077 \cdot k \cdot F \cdot r_k^2}{10000 \eta_{mp} \cdot \rho \cdot (i_k \cdot i_0)^2} (a + b \cdot n_e + c \cdot \varphi + d \cdot n_e^2 + e \cdot \varphi^2 + f \cdot n_e \cdot \varphi) n_e^2 \quad (9)$$

Dependence (9) represents the dependence of fuel consumption on FIAA and CS rotation speed, drive ratio of GB, truck weight, road conditions, and other parameters.

The next stage of optimal control system development lies in selection of the target function (optimality criterion). Optimization is performed based on the minimum fuel consumption and minimum time of transportation. At that these parameters are mutually exclusive, i.e. minimum transportation time is achieved at minimum fuel consumption and vice versa. Based on uniqueness principle [8], the optimality criterion will be a linear combination of two targeted functions:

1. minimum fuel consumption criterion  $Q_p = f(n_e, \varphi) = \min$ ;
2. minimum travelling time criterion  $t = f(\vartheta_a) = \min$ .

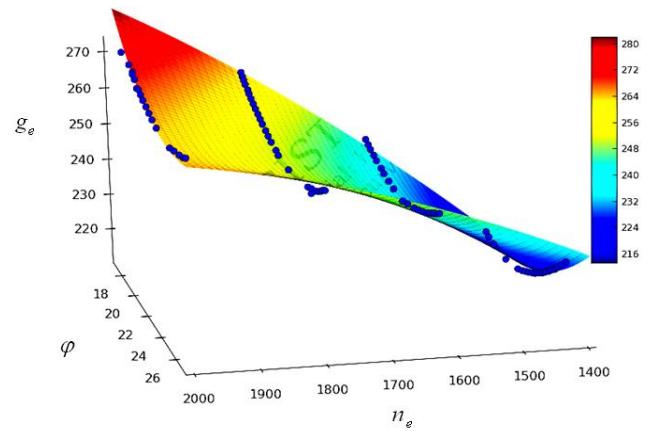


Fig. 3. Dependence of fuel specific consumption on FIAA and CS rotation speed

After combining of these criteria the following criterion could be obtained:

$$Cf = p_1 \cdot Q_p + p_2 \cdot t \quad (10)$$

Where  $p_1$  and  $p_2$  – weight of optimal criteria importance. We assume  $p_1 + p_2 = 1$ .

The minimum travelling time is achieved by the increase of travelling speed.

So, optimal control could be represented as an optimization problem:

$$Cf = p_1 \cdot Q_p + (1 - p_1) \cdot \frac{1}{\vartheta_a} = \min \quad (11)$$

when the following conditions are satisfied:

1. Mathematical model of fuel consumption is represented by dependence (9);
2. Mathematical model of truck travelling speed is given by dependence (2); and following limitations:
  - $n_{e\min} < n_e < n_{e\max}$ ,
  - $\varphi_{\min} < \varphi < \varphi_{\max}$ .

In the process of solving the assigned task we will obtain the optimal values of FIAA and CS rotation speed at a definite gear. In the picture 4 the example of dependence of targeted function on CS rotation speed at FIAA fixed value  $\varphi$ , and weight of importance  $p_1$  for different gears  $i_k$  is given.

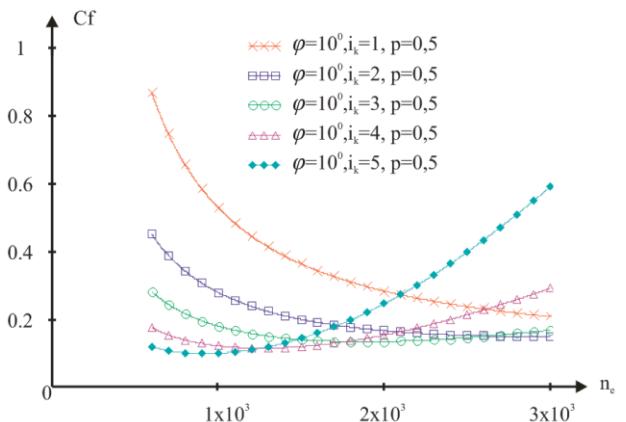


Fig. 4. Dependence of targeted function on FIAA values, CS rotation speed, and definite gear

As we see from the picture 1, optimal control system allows evaluating of diesel engine fuel equipment technical condition (blocks 8, 9, 10). In the process of motor transport exploitation the wearing of fuel equipment spare parts occurs, causing deviation of parameters from normal values. By way of evaluating of these deviations, the wear rate of fuel equipment could be determined. FIAA was selected for such an evaluation.

Evaluation of fuel equipment condition is performed based on the following formula:

$$Z = \frac{|\varphi_{opt} - \varphi_{izm}|}{\Delta\varphi_{max}} \cdot 100\% \quad (12)$$

where  $Z$  – evaluation of fuel equipment technical condition,  $\varphi_{opt}$  – optimal value of FIAA,  $\varphi_{izm}$  – measured values of FIAA,  $\Delta\varphi_{max}$  – maximum allowed deviation of FIAA from the nominal value.

#### 4. Conclusions

So developed optimal control system allows automating of motor transport control process in accordance with optimality criterion, thus allowing not only reducing of human factor influence for the process of motor transport driving, but also reducing of fuel consumption, not only reducing the negative influence of motor transport for environment, but also performing approximate evaluation of fuel equipment technical condition of truck diesel engine.

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## DEFINITION OF THE OBJECTS OF MULTIVARIABLE CONTROL OF TECHNOLOGICAL PROCESS OF SMELTING INDUSTRY ON THE BASIS OF OPTIMIZATION MODEL

**Shamil Koshymbaev<sup>1</sup>, Zhibek Shegebaeva<sup>1</sup>, Waldemar Wójcik<sup>2</sup>**

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**Abstract.** This article analyzes work of metallurgical shop as a complex control object. It also includes description of copper complex and synthesizes three-level structure of control system. Technical and economical indexes and also control object are defined in this article.

**Keywords:** metallurgical plant, copper, matte, management tasks

### DEFINICJA OBIEKTÓW WIELOWYMIAROWEGO STEROWANIA PROCESAMI TECHNOLOGICZNYMI W HUTNICTWIE NA PODSTAWIE MODELU OPTYMALIZACJI

**Streszczenie:** W artykule przedstawiono analizę pracy przemysłu metalurgicznego rozpatrywanego jako złożony obiekt sterowania. Opisano kompleks hutniczy i syntetyzowaną trójwarstwową strukturę systemu sterowania. Określono wskaźniki techniczno-ekonomiczne i sformułowano zadania sterowania.

**Słowa kluczowe:** zakład metalurgiczny, miedź, matowe szkło, zadanie sterowania

### Introduction

Metallurgical shop includes production areas, designed for electric smelting of copper concentrates, matter conversion and fire refining of blister copper.

Raw material input is copper-bearing stock, including granules, recyclable materials and feed-adjusting mixture (limestone and pyritic concentrate). Stock is fed in twin furnaces and melts by the heat, released in slag path. Melted material

is divided into matte and waste slag during settling. While accumulation slag is fed from the process area into disposal area and matte is sent to converting area for further recycling.

This process includes removal of sulphur from matte and converts it into gases as SO<sub>2</sub>. Iron is scorified. To create necessary slag adjustment siliceous ore(flux metal) is loaded into convertors. Process scheme and interrelation between tasks is shown on Figure 1.

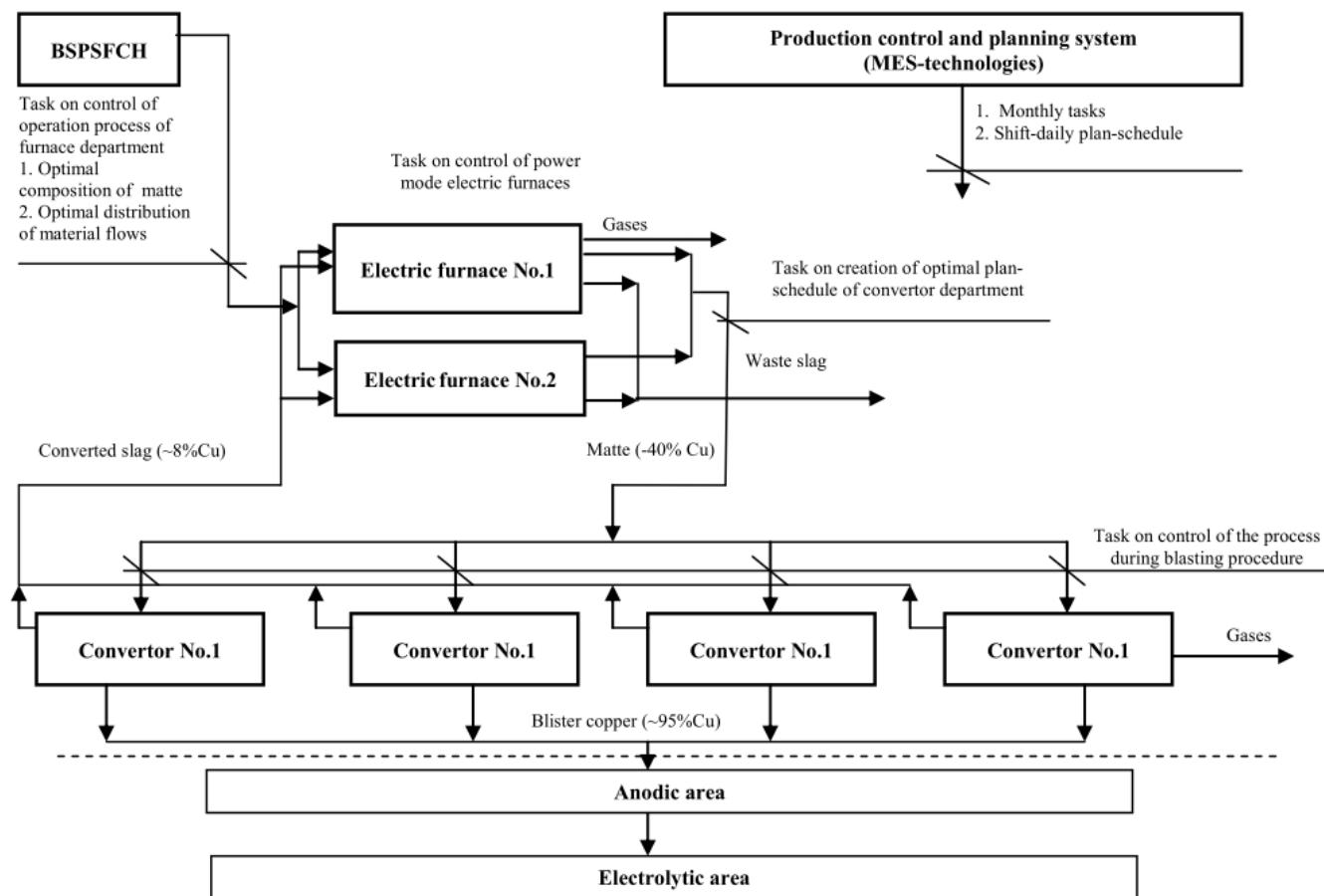


Fig. 1. Process scheme and task interrelation

Converting process refers to the class of discrete-continuous, cyclic, multi-stage processes and is characterized by autogenic operation with heat release. The latter allows additional recycling of cold materials (matte skins). Products of convertor smelting are blister copper, converted slag, released gases and dust. Converted slag is returned back to electric furnaces for copper extraction and gases are fed for production of sulphuric acid after their cleaning from dust [5].

Blister copper is subject to fire refining in anodic furnaces. Solid blister copper, anodic residuals, defective anodes and copper scrap are also loaded into anodic furnace. Process of fire refining refers to the class of discrete-continuous, cyclic, multi-phase processes. Smelting product, refined (anodic) copper is sent to electrolysis department in the form of anodes and anode slag is loaded into converters.

Considered copper-smelting complex is characterized by a number of peculiarities as control object, namely:

- a) Discrete-continuous nature of production. Thus manufacturing chain includes discrete, periodic process (converting and fire refining) along with continuous processes (smelt furnaces).
- b) Series parallel structure with technological cross (between parallel flows) and reverse relations in the system that complicates coordination of work of adjacent departments and strengthen interconnections between them.
- c) Large tonnage, high power consumption and considerable length of production chains, resulting in large dynamic and transport delays. Thus, in accordance with results of studies, delay in terms of stock-matte channel is 6-7 hours and 8-9 hours in terms of stock-slag channel.
- d) Broad range and high level of external and internal disturbances that result in random nature of processes and different degrees of uncertainty at different time intervals. It is conditioned by considerable fluctuations in characteristics of feed streams and industrial products, drift of characteristics of process scheme aggregates etc.

## 1. Decomposition of task

Synthesis of the structure of shop control tasks uses decomposition approach to arrangement of control system structure. Decomposition of general task model, allowing its splitting into several hierarchically interconnected submodels, is realized in accordance with principle of space-time decomposition by multiple areas (aggregates) and multiple time intervals, considering dynamic properties of control objects and frequency characteristics of disturbing effects. Thus we obtain hierarchical multi-level structure of control tasks.

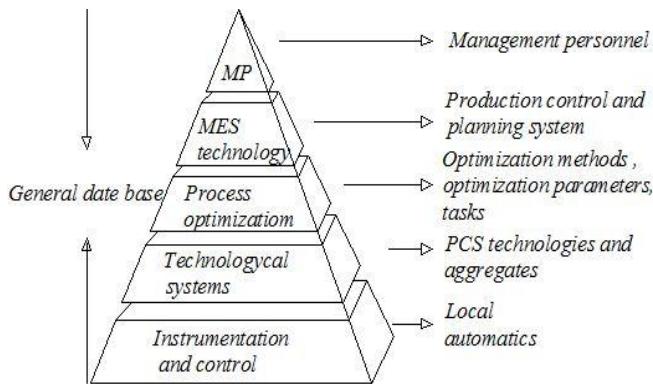


Fig. 2. Levels of control of copper smelting department

The upper level deals with tasks of operational control of copper-smelting complex of metallurgical plant, composed of the following subtasks: distribution of loads between electric furnaces, creation of plan-schedule for converter and anode departments. The main aim of subtasks at this level is specification of daily plan, generated by MES technology system and divided up to aggregate tasks [10].

Results of solution of upper level tasks determine requirements to the second level, i.e. control over separate processes and aggregates (Electric smelting, converting and anodal smelting).

Lower level of control structure is represented by the tasks of stabilization of electric melting condition and control of converting level during blowing [7].

## 2. Technical and economical nature and definition of control tasks

### Metallurgical plant operational control subsystem

Arrangement of rhythmical and coordinated operation of the areas and aggregates of metallurgical plant should be ensured by technological process operational control system that forms and realizes plan-schedule of the plant.

Daily plan-schedule of metallurgical plant defines distribution of loads between electric furnaces, distribution of matte between other converters, beginning and completion of converter melting, distribution of blister copper between separate anodic melting processes, beginning and completion of anodic melting. Plan-schedule should ensure qualitative and quantitative execution of daily plan on production of matte, blister and anodic copper, determined by production planning and control system (MES technologies). The task of plan-schedule is reduced to the task of discrete programming of high dimension. Due to this act there is a need in decomposition of above-mentioned task. As a result of decomposition the solution of the task relating to creation of optimal plan-schedule of metallurgical plant is reduced to solution of the following subtasks:

- Planning of optimal plan-schedule of anodic department, ensuring smooth operation of production area.
- Planning of optimal plan-schedule of converter department, ensuring smooth operation of production area and execution of daily plan on production of blister copper and recycling of cool materials;
- Optimal distribution of material flows between electric furnaces and determination of chemical composition of feed-adjusting mixture, minimizing relative losses of copper in electric furnace department [8].

### Electric smelting process control subsystem

Task on control of process conditions of electric smelting, considering specifics of stock preparation area (availability of pile) is split into two tasks, to be solved in different time intervals.

Chemical composition of stock is determined by ratio and chemical composition of material flows, entering electrical furnace (granules, limestone, pyrites etc.). The main role is taken by chemical composition of granules (it accounts for 70-80% of stock weight), which is realized in stockyard through mixing of Zhezkazgan and pyritic concentrates, limestone and other materials. Random fluctuations in composition of granules takes place during production of piles (46 days) and chemical composition of granules considerably deviates (2-4%) from average optimal value, determined for pile, in short intervals of control (shift) [4].

Due to above-mentioned, the task of control of electric welding process condition is split into two tasks, to be solved in different time intervals:

Determination of the optimal composition of pile in time interval of its filling (4-6 days);

Operational (during shift) distribution of lows between furnaces, determining current optimal granular flow, feed-adjustment mixture and its chemical compositions [9].

The task on optimization of chemical composition of pile can be formulated in the following way: to determine chemical composition of pile that minimizes losses of copper with waste slag of electric furnace department, considering limits of qualitative values of smelting products, i.e. matte and slag.

Solve the task on the basis of mathematical model of complex "stock-blister copper" [2].

Task on control of power mode of electric furnace can be formulated in the following way: considering set (current) flow values and chemical composition of stock, determine electrode burial depth (conductivity under electrodes), minimizing rated power consumption at smelting rate limits, losses of copper with waste slag, total capacity of furnace, phase voltage, height of slag and matte baths and also electrode burial depth in melted slag.

### 3. Converting process control subsystem

Availability of inverse relation of the process through convertor slag considerably effects technical and economical values of production in general. Thus, total copper extraction in metallurgical plant considerably depends on amount of copper in recycled material (converted slag). Concentration of copper in slag mainly depends on concentration of copper in converted mass, siliceous slag and its temperature [1].

Melt temperature during smelting procedure depends on enrichment degree of mass in every blasting and also value of blast rate during blasting procedure. Necessity in obtaining of set volume of copper per melting procedure and coordinated operation of processing units determine need in control (planning of plan-schedule) of sequence of converter blasting procedures with determination of their duration, number and consumption of recycled materials per every blasting procedure.

In accordance of above-mentioned we point out solution of two interrelated tasks: control of the process during blasting and control of converter smelting [3].

Task on control of converting process can be formulated in the following way: basing on current state of the process it is necessary to make decision on continuation or ceasing of blasting procedure. If blasting procedure, determined by process and structural limits, is continued, it is necessary to determine blast and ore flow in current control interval that should be optimal in terms of criteria, considering deviations from set values of blast flow, melt temperature and content of silica in slag. The task on control of converter smelting can be formulated in the following way: to determine plan-schedule of converter smelting that fixes duration of blasting, amount of matte, ore and average blast flow per every blasting procedure that should be optimal in terms of criteria, considering amount of copper in convertor slag, deviations from set values of melt temperature and concentration of silica in slag [6].

### 4. Conclusion

Tasks on control of metallurgical complex and separate technologies, formulated above, are included into requirements specification of ACS of copper plant JSC "Kazakhmys".

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## SYNTHESIS OF MANIPULATION ROBOT PROGRAM TRAJECTORIES WITH CONSTRAINTS IN THE FORM OF OBSTACLES

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**Abstract.** The paper presents a method of synthesis of manipulation robot motion trajectory according to mobility degrees. The configuration of the manipulator parts and obstacles are approximated by semiinfinite spaces limited by planes. The fact of robot collision with obstacles is reduced to the problem of determining the compatibility of systems of linear inequalities. The authors developed an algorithm for solving the problem based on dynamic programming method.

**Keywords:** robot trajectory, the degree of mobility, the manipulator

### SYNTEZA TRAJEKTORII PROGRAMOWYCH ROBOTA MANIPULACYJNEGO PRZY OGRAŃCZENIACH W POSTACI PRZESZKÓD

**Streszczenie.** Przedstawiono metodę syntezy trajektorii ruchu robota manipulacyjnego wg stopni swobody. Konfiguracja położenia robota i przeszkód jest przybliżona półprzestrzenią ograniczoną płaszczyznami. Fakt zderzenia robota z przeszkodami ograniczono do problemu określenia zgodności systemów nierówności liniowych. Opracowano algorytm rozwiązywania zadań na podstawie metody programowania dynamicznego.

**Słowa kluczowe:** trajektoria robota, stopnie swobody, manipulator

### Introduction

In general, a manipulation robot is an open-loop kinematic system consisting of elements and linkage joints connecting them in series [5]. Geometric dimensions of elements, type of joints and range of their movements set the workspace at any point of which a robot gripper can be positioned. The type of joint is determined by structural features and capabilities of manipulation robot actuators. As a rule, they represent Grade 5 kinematic pairs, and can be set by logical variables  $p_i$ :

$$p_i = \begin{cases} 1, & \text{in case of translatory movement,} \\ 0, & \text{in case of rotary movement} \end{cases} \quad (1)$$

The variable determining the position and orientation of the gripper within the workspace are the values of generalized coordinates  $q_i$ ,  $i=1,2,\dots,n$ , according to robot degrees of mobility, where  $n$  is the number of degrees of mobility.

### 1. Methodology for objects formal description

The problem of synthesis of program robot trajectories is to determine the values of generalized coordinates by mobility degrees providing moving the gripper along the predetermined trajectory with a given accuracy, if the conditions of mutual non-collisions of elements with each other and with barriers in technological space, i.e. in the space where they can move while the robot performs processing operations. Since a robot consists of a body and elements representing geometric objects moving in technological space containing obstacles also representing geometric objects, it is necessary to develop a technique of their formalized description. For this purpose a manipulator robot is represented as a complex geometric object consisting of a number of geometric subobjects: a fixed base and movable elements, element 2, ..., element  $n$ , the position of each of which is determined by the values of the generalized coordinates. Each subobject is described as logical expressions  $R_b(x, y, z)$ ,  $R_l^1(x, y, z, q_1)$ ,  $R_l^2(x, y, z, q_1, q_2)$ , ...,  $R_l^n(x, y, z, q_1, q_2, \dots, q_n)$ , which are respectively: the basis, element 1, element 2, ..., element  $n$ . Obstacles existing in the technology space are also represented as a number of fixed geometric objects that are described in the form of logical expressions:  $R_p^1(x, y, z)$ ,  $R_p^2(x, y, z)$ , ...,  $R_p^m(x, y, z)$ , respectively, where  $m$  is the number of obstacles.

The logical function describing a geometric object has the following form [4]:

$$R(x, y, z) = R_1 L R_2 L \dots L R_N = 1, \quad (2)$$

$R_k$ , ( $k=1,2,\dots,N$ ) are the logical variables defined by the following expression:

$$R_k = \begin{cases} 1, & B_k(x, y, z) \leq 0, \\ 0, & \text{otherwise.} \end{cases}$$

where  $B_k(x, y, z) \leq 0$  is the inequality setting or approximating the  $k$  part of the edge of a geometrical object;  $N$  is the number of inequalities;  $L$  – the signs of logical operations of conjunction, disjunction or negation. We approximate the given trajectory of the gripper by a set of points  $A_j(x_j, y_j, z_j)$ ,  $j=1,2,\dots,m$ , where  $m$  is the number of points approximating the trajectory. The distance between neighboring points  $d_{j,j+1}$  is defined on the basis of condition of magnitude constancy of the trajectory curvature:

$$K = \frac{\alpha}{d_{j,j+1}},$$

Where  $\alpha$  is the magnitude of change in the angle of the unit vector of tangents in points  $A_j(x_j, y_j, z_j)$  and  $A_{j+1}(x_{j+1}, y_{j+1}, z_{j+1})$ ;  $K = \text{const}$ , depth of camber ratio.

Let there be given a configuration of robot kinematics scheme determined by the vector  $Q^j(q_1^j, q_2^j, \dots, q_n^j)^T$ , and the position of the gripper in points  $A_j(x_j, y_j, z_j)$  in the coordinate system related to the fixed base of the robot. It is necessary to determine the vector  $Q^{j+1}(q_1^{j+1}, q_2^{j+1}, \dots, q_n^{j+1})^T$  providing moving the gripper to another point  $A_{j+1}(x_{j+1}, y_{j+1}, z_{j+1})$  defined in the same coordinate system. Then, posing the problem of synthesis of manipulation robot trajectories by mobility can be represented as follows:

It is necessary to minimize (maximize) the kinematic quality criteria [2]:

$$J = \sum_{j=1}^{m-1} \sum_{i=1}^n C_i (q_i^j - q_i^{j+1})^2 \rightarrow \min(\max), \quad (3)$$

while the constraints define the condition point entries approximating the trajectory into the robot manipulation workspace of [4]:

$$\forall A_j(x_j, y_j, z_j), j=1,2,\dots,m : D_1 L D_2 L \dots L D_M = 1 \quad (4)$$

where  $C_i$  is the coefficient characterizing the dynamic indicators of the drive of the  $i$ -th degree of mobility according to a predetermined parameter (energy consumption, speed, accuracy, etc.);  $q_i^j, q_i^{j+1}$  - elements of vectors  $Q^j$  and  $Q^{j+1}$  correspondingly,  $D_k$ , ( $k=1,2,\dots,M$ ) - logical variables defined by the following expression:

$$D_k = \begin{cases} 1, & B_k(x, y, z) \leq 0 \\ 0, & \text{otherwise} \end{cases},$$

where  $B_k(x, y, z) \leq 0$  - the inequality defining or approximating the  $k^{\text{th}}$  part of the manipulation robot workspace,  $M$  - the number of inequalities, as well as additional constraints, taking into account possible mutual collision of robot elements (5) and robot elements with obstacles (6):

$$R_b \wedge R_1^1 \wedge R_1^2 \wedge \dots \wedge R_1^n = 0, \quad (5)$$

$$(R_b \vee R_i^1 \vee R_i^2 \vee \dots \vee R_i^n) \wedge (R_p^1 \vee R_p^2 \vee \dots \vee R_p^N) = 0, \quad (6)$$

where  $n$  is the number of manipulator elements,  $N$  is the number of obstacles in the technology space. For practical implementation of synthesis algorithm based on possible mutual collisions of elements and robot elements with the existing in the working area obstacles it is necessary to determine the fact of collision. For this purpose the obstacles located in the working area, and the robot elements are approximated by polyhedra described by the systems of linear inequalities (7):

$$\begin{cases} a_{1,1}^k x + a_{1,2}^k y + a_{1,3}^k z + a_{1,4}^k \geq 0, \\ a_{2,1}^k x + a_{2,2}^k y + a_{2,3}^k z + a_{2,4}^k \geq 0, \\ \dots \\ a_{m,1}^k x + a_{m,2}^k y + a_{m,3}^k z + a_{m,4}^k \geq 0. \end{cases} \quad (7)$$

where  $a_{i,j}^k$ ,  $j=1,2,3,4$ ,  $i=1,2,\dots,m$ , are the coefficients defining the faces of the polyhedron in space OXYZ, approximating the  $k^{\text{th}}$  obstacle (element).  $m$  is the number of faces of a  $k^{\text{th}}$  polyhedron. Then the mutual collision of the  $i^{\text{th}}$  obstacle (element) of the manipulation robot with the  $k^{\text{th}}$  obstacle (element) is determined by the condition of the existence of solution of the following system of linear inequalities:

$$\begin{cases} a_{1,1}^k x + a_{1,2}^k y + a_{1,3}^k z + a_{1,4}^k \geq 0, \\ a_{2,1}^k x + a_{2,2}^k y + a_{2,3}^k z + a_{2,4}^k \geq 0, \\ \dots \\ a_{m,1}^k x + a_{m,2}^k y + a_{m,3}^k z + a_{m,4}^k \geq 0, \\ a_{1,1}^l x + a_{1,2}^l y + a_{1,3}^l z + a_{1,4}^l \geq 0, \\ a_{2,1}^l x + a_{2,2}^l y + a_{2,3}^l z + a_{2,4}^l \geq 0, \\ \dots \\ a_{n,1}^l x + a_{n,2}^l y + a_{n,3}^l z + a_{n,4}^l \geq 0. \end{cases} \quad (8)$$

Using known methods of the theory of linear algebra we can determine the fact of the collision of manipulation robot elements with existing obstacles and the robot elements among themselves that arises from the condition of compatibility of the system of linear inequalities (8) [3]. One way of solving the problem is to compute all possible minors 3 of the system of linear inequalities (8). If there is a minor different from zero, then the system (8) is not compatible, i.e. there is no fact of collision of elements among themselves and with the obstacles existing

in the working area. This problem can also be solved using the theory of matrices, based on the Kronecker-Capelli theorem [3]. The initial system of inequalities (8) by adding free variables is reduced to systems of linear equations. The coefficient matrix rank and the rank of the augmented matrix are calculated. When there is a coincidence, the system has at least one solution; otherwise there is no solution.

The algorithm of synthesis of program trajectories by robot manipulation mobility based on mutual collisions of robot elements and robot elements with the obstacles in the working area consists of two stages. At the first stage of the algorithm there is built a weighted graph whose vertices are the possible values of  $q_i$ , and the edges correspond to the kinematic pairs. At the second stage, basing on Bellman dynamic programming method we find the set  $Q(q_{i,j})$  that minimizes the criterion of quality (3).

Identification of possible values of  $q_i$  with sampling interval  $\Delta q_i$  depends on the type of the robot kinematic pair, i.e. on the values of the parameter  $p_i$ ,  $p_{i+1}$ .

Let us describe the sections of the working space formed by the movement of the elements, starting from the  $r^{\text{th}}$  degree of mobility of the manipulator robot, in the form of a logical expression:

$$L_r = D_1 L D_2 L \dots L D_m = 1, \quad (9)$$

where  $D_k$ , ( $k=1,2,\dots,m$ ) are the logical variables specifying or approximating a section of manipulation robot workspace.

Expression (9) is obtained as follows: using lengths of elements,  $i = 1, 2, \dots, n$ ; parameters of joints  $p_1, p_2, \dots, p_n$ , as well as considering the design constraints imposed on the changes of values of the generalized coordinates:

$$q_i^H \leq q_i \leq q_i^B, \quad (10)$$

where  $q_i^H$ ,  $q_i^B$  - lower and upper values of the generalized coordinate of the  $i^{\text{th}}$  degree of mobility of the manipulator. It is necessary to show a section of the robot workspace graphically. The resulting graphical representation is used to determine the elementary surfaces limiting the workspace section described by logical variables  $D_k$ . Linking the variables  $D_k$ , in accordance with the obtained graphical configuration of a part of the workspace, we obtain an expression of the form (9). Suppose that we are given the initial configuration of the kinematic scheme which ensures the condition of non-collision of robot links among themselves and with barriers in technological space.

## 2. Algorithm of programmed trajectories synthesis

The algorithm is based on the analysis of the ways in the weighted graph containing all possible solutions and has the following form:

Step 1. Entering initial values: the coordinates of points approximating the trajectory of the gripper  $A_j(x_j, y_j, z_j)$ ,  $j=1,2,\dots, m$ ; logical expressions  $L_1, L_2, \dots, L_{n-2}$  describing the working space and the subspaces; logical expressions:

$$R_p^1(x, y, z), R_p^2(x, y, z), \dots, R_p^m(x, y, z),$$

$$R_b(x, y, z),$$

$$R_i^1(x, y, z, q_1), R_i^1(x, y, z, q_1, q_2), \dots, R_i^1(x, y, z, q_1, q_2, \dots, q_n)$$

describing the obstacles, the robot base and links as geometric objects;  $\Delta q_1, \Delta q_2, \dots, \Delta q_n$  magnitude steps of finding a solution by mobility;  $Q^u(q_1^u, q_2^u, \dots, q_n^u)^T$ ,  $Q^l(q_1^l, q_2^l, \dots, q_n^l)^T$  - the vectors defining lower and upper values of change of the generalized coordinates values; the initial position of the manipulation robot configuration  $Q^0(q_1^0, q_2^0, \dots, q_n^0)^T$ .

Step 2. If the condition

$$\forall A_j(x_j, y_j, z_j), \quad j=1, 2, \dots, m: \quad L_1 = 1$$

is satisfied, then go to Step 3, otherwise the problem has no sense and the solution is over.

Step 3.  $j=1$

Step 4. By each mobility degree the interval of change of the generalized coordinates is divided into  $n$  equal intervals. As a result of this procedure we receive the digraph of possible configurations. We define this graph by a triangular adjacency matrix of dimension  $(nm+2 \times nm+2)$ , where  $n$  is the number of robot mobility degrees,  $m$  is the number of generalized values satisfying the condition (12), the adjacency matrix elements are determined based on the following expression:

$$a_{i,j}^{i+1,j} = \begin{cases} 1, & \text{if vertex } q_{i,j} \text{ is adjacent to vertex } q_{i+1,j}, \\ 0, & \text{otherwise.} \end{cases}$$

Step 5. For each possible configuration of the manipulation robot we verify the condition  $R_b \vee R_l^1 \wedge R_l^2 \wedge \dots \wedge R_l^n = 0$ , then the value  $a_{i,j}^{i+1,j} = 1$ , otherwise  $a_{i,j}^{i+1,j} = 0$ .

Step 6. For each possible configuration of the manipulation robot we verify the condition:

$$(R_b \vee R_l^1 \vee R_l^2 \dots \vee R_l^n) \wedge (R_p^1 \vee R_p^2 \vee \dots \vee R_p^m) = 0,$$

then the value  $a_{i,j}^{i+1,j} = 1$ , otherwise  $a_{i,j}^{i+1,j} = 0$ .

Step 7. Further we again define the values  $q_{i,j}$  based on the following expression:

$$q_{i,j} = \min \sum_{j=1}^m C_i (q_i^0 - q_{i,j})^2.$$

Step 8. For the final vertex of the graph we have:

$$q^\kappa = \min \sum_{j=1}^n C_n (q_n^0 - q_{n,j})^2$$

Step 9.  $j = j+1$ .

Step 10. If  $j \leq n$ , then go to Step 4, otherwise to Step 11.

Step 11. We derive the values of the generalized coordinates by robot mobility of the vector  $Q(q_{i,j})$ .

Further the problem is solved according to a well-known scheme [2, 5]. On the basis of the solution of the inverse problem by statute using the method of spline functions in the space

of generalized coordinates we can obtain the trajectory that ensures coincidence of the grip with program movement at the points approximating the motion trajectory. Then given the constraints on the velocity and acceleration, we obtain the manipulation robot control program.

The analysis of the obtained solution can be made as follows: we describe the robot links and obstacles with a reserve [2], i.e. these geometric objects are placed in the spaces completely covering them and also described by systems (7), (8). Then the robot is moved along a predetermined path based on control programs; and at each sampling interval it is analyzed for consistency with newly acquired, with respect to the entered reserve, systems of equations (7), (8). In this case, if no collisions are detected during the robot movements, the control program is admissible and optimal according to the selected criterion (3).

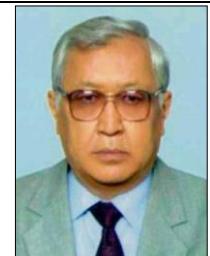
### 3. Conclusions

The proposed approaches for solving the problem of synthesis of manipulation robot movements allow avoiding some of the disadvantages (solvability condition, redundancy of solutions, the possibility of practical implementation, etc.) of the known approaches [2, 5].

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## BUILDING OPTIMAL BOUNDARY CONTROL BY THE SUCCESSIVE APPROXIMATIONS METHOD

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*Abstract.* The article suggests a method for calculating the boundary control in the tape bearings optimal program using the method of successive approximations.

**Keywords:** optimal control, boundary conditions

### OPRACOWANIE OPTYMALNEGO STEROWANIA Z OGRANICZENIAMI Z WYKORZYSTANIEM METODY KOLEJNYCH APROKSYMACJI

*Streszczenie:* Przedstawiono metodę opracowania optymalnego sterowania z ograniczeniami w taśmociągach z wykorzystaniem metody kolejnych aproksymacji.

**Słowa kluczowe:** sterowanie optymalne, warunki graniczne

### Introduction

Technical systems with gas dynamic lubrication processes have been widely applied at modern enterprises of mechanical engineering, textile industry and instrumentation. Gas lubrication has interesting and important applications in different types of bearings, in particular in the so-called tape bearings (TB). Lubrication of tape bearings by air or some other gas provides advanced technical solutions giving significant advantages over other engineering systems. In technical systems lubricated by air friction is much lower. The wear and tear of tape bearings lubricated by air or gas considerably decreases. The use of an external gas or air supply under pressure significantly expands the scope of application of such tape bearings, as they successfully work at both low and high speeds and efforts.

Tape bearings are often used in processes of continuous production and processing of plastic film, metal ribbon, paper, textile materials and fibers. Tape bearings are used in self adjusted supports of increased stability for high-speed rotors.

The processes taking place in tape bearings are generally described by systems of partial combined equations relative to the main inter-related parameters characterizing the state of tape bearings. These parameters are primarily: thickness of the air film between the flexible and rigid surfaces; overpressure generated by the relative motion of two surfaces or external power; and tension of the flexible tape in their area of interaction through a thin layer of air. The processes taking place in tape bearings are complex physical and mechanical processes; so the desired state of tape bearings with the required values of the basic parameters in the area of interaction of flexible and rigid surfaces is not always achieved in practice. Specific numerical values of these parameters depend on the most number of factors and may go beyond the permitted values in the process of work. The task of more accurate calculation of tape bearing parameters and keeping them within the necessary range is of current interest.

The performance of specified technical systems can be achieved through continuous search for the best conditions of the processes on the basis of fast processing of information about their condition, as well as an optimal process control strategy in real time.

Solving these problems is possible on the basis of the apparatus of mathematical physics and the theory of optimal control of processes with distributed parameters. The mathematical aspects of this problem were dealt with in the papers by A.G. Butkovsky [3, 4], and T.K. Sirazetdinov [9], K.A. Lurye [7], J.L. Lions [6], and other researchers.

Many problems of control of objects with distributed parameters are characterized by the fact that the spatial variations of the object parameters in the evaluation of dynamic properties

of processes in the object are fully determined by the boundary conditions of the boundary value problem. The control problem is reduced to the problem of control of the border state or boundary control problem. The mechanism of any boundary control is reduced to the formation of such boundary conditions under which the processes occurring in the object give the desired result.

The mathematical theory of optimal boundary control in systems with distributed parameters was developed in works [5, 6, 8, 9, 10, 11, 12, 13].

The problems of programming open-loop control have been considered in hydrodynamics in connection with the fluid flow stabilization problem in the boundary layer. It was proposed to control the flow in the boundary layer by drawing heat off from the surface of the stream-lined body [1], the suction of fluid through porous streamlined body surface [2], as well as traveling elastic wave generated on the surface of the body. The issues of boundary control in closed-loop control systems with distributed parameters have been considered in the problems of stabilization of unstable states in plasma, hydrodynamics, charged particle beams with feedback operators implemented in the boundary conditions of distributed control systems and provide suppression of these unstable states [7].

However, the range of solved problems of boundary control of complex physical and mechanical processes does not include complex technical systems consisting essentially of the physical processes of different nature. Tape bearings described by the Reynolds equation and the equation of the moment-free shell state may be an example.

### 1. Statement of the problem

The main content of the optimal control problem is the selection of one of various possible implementations of the considered process which would provide for the best process according to some pre-specified criterion. A possibility of choice of different realizations of a process is conditioned by the presence of controls by modifying which we can interfere in its course and apply the desired trajectory. As a rule, this situation is mathematically expressed by the fact that a set of mathematical relations describing processes includes parameters that can be changed within certain limits. In a particular case these parameters may be included in the boundary conditions of the problem and thus affect the behavior of the solution of the constitutive equation.

Let us consider the quasi-static formulation of the problem of calculating the optimal control program. The calculation of the optimal boundary condition of the program for distributed systems in a quasi-static formulation allows the use of modern numerical methods for solving nonlinear partial differential equations using

the necessary extremum conditions. These methods are aimed at finding a function that directly meets the necessary and sufficient conditions of optimality. The problem of finding the minimum of the function by means of the necessary conditions is reduced to the problem of finding the roots of the function. And the problem of calculating the optimal boundary of the program is reduced to the solution of boundary value problems for systems of ordinary differential equations. They are easy for programming and allow the use of simple standard programs. This method is similar to the so-called method of adjoint equations with a free right end, yet taking into account the specifics of the boundary control and the restrictions on the control actions. When constructing optimal boundary control, an efficient method of successive approximations is used. There are many methods of successive approximations, such as Euler method, Ritz method, Kantorovich method, and the so-called direct methods to minimize the functional so that it took the smallest possible value.

$$I = \int_{\Omega_0}^{\Omega_k} [Q(\Omega, t) - Q^*(\Omega, t)]^2 d\Omega \quad (1)$$

Here  $\Omega$  is the current angular coordinate,  $t$  is the current time,  $Q(\Omega, t)$  is the actual state of the controlled parameter,  $Q^*(\Omega, t)$  is the desired state of the controlled parameter. In all the above said cases it is necessary to calculate the functional gradient. Since the controlled object is described by partial differential equations, the computation of the gradient is reduced to the calculation of the partial derivatives on all the variables included in the minimized functional. In the numerical implementation these operations are quite time-consuming and take up much CPU time, thus making the use of modern computers inefficient. For efficient calculation of the gradient we use the approach which allows taking into account the specifics of the boundary control and solving the optimization problem while reducing the number of computational procedures. The reduction in computation and consideration of the specificity of a solved problem can be made at the expense of the conjugated system, and more exactly with the use of necessary and sufficient conditions of optimality. For this problem with extra conditions that impose restrictions on control action of the type:

$$V[U_r(t)] < 0 \quad (r = 1, \dots, m) \quad (2)$$

we construct an algorithm of optimal boundary control. Thus we formulate the problem as follows. In the plane  $\Omega, t$  there is a rectangular area  $D_{ab}$ , in which systems of differential equations are given.

$$\frac{\partial Q_i}{\partial \Omega} = f_i(\Omega, Q) \quad (i = 1, \dots, n) \quad (Q = Q_1, Q_2, \dots, Q_N) \quad (3)$$

On the boundary  $\Gamma$  function  $Q_i$  is subject to boundary conditions of the first order

$$Q_i(\Omega, t) = Q_i(t) \quad t > 0 \quad (4)$$

The control variables in this system are some of the main parameters included in the boundary conditions

$$Q_r(\Omega_0, t) = Q_r(t) \quad (r = 1, \dots, m < n) \quad (5)$$

Due to the fact that the controlled parameter changes differently with time, the value of  $Q_i$  is a function of the two variables  $Q_i = Q_i(\Omega, t)$ . By varying the boundary values  $U_r(\Omega_0, t)$  subject to the condition (2) it is necessary to select their meaning so that the criterion (1) had the smallest value for an arbitrary time  $t$ .

## 2. Solution of the problem of optimal boundary control

We divide the spatial coordinate  $\Omega$  and the time coordinate  $t$  into small segments. The segment  $[\Omega_0, \Omega_k]$  into  $M$  parts by the points  $\Omega_0 = 0, \Omega_1, \Omega_2, \dots, \Omega_m = \Omega_k$ ; and the segment  $[0, t]$  - into the  $N$  parts by the points  $t_0 = 0, t_1, t_2, t_3, \dots, t_n = t$ . Then we draw the right lines parallel to the coordinate axes  $\Omega$  and  $t$  via the

ends of each of the segments  $[\Omega_0, \Omega_k]$  and  $[0, t]$  lines. Then the rectangular area  $D$  will be divided into  $MN$  small rectangular areas  $D_{ab}$  ( $a = 1, 2, \dots, M$ ;  $b = 1, 2, \dots, N$ ). We shall look for the optimization problem solution in the set of control functions  $Q_r(\Omega_0, t) = U_r(t)$  ( $r = 1, 2, \dots, m < n$ ) of the constants in each small area  $D_{ab}$ , and uniques  $Q(\Omega, t)$  providing condition (4). Thus, the solution of the formulated problem is reduced to minimizing the function  $I(U_{rb})$  of  $Nm$  variables, where

$$I(U_{rb}) \quad (6)$$

are defined by (1), provided that the system (3) was solved in  $U_r(\Omega_0, t) = U_b(\Omega_0, t)$  for  $D_{ab}$ . Thus we have the problem of minimizing the function of a finite number of variables. If we use the gradient method, it is necessary to make calculations by the formula (6)  $Nm$  times, i.e. to solve a system of differential equations (3)  $Nm$  times. However, if we use the necessary optimality conditions for the determination of the first variation of the variables of Functional  $I$  on variables  $U_r^b$ , it is possible to organize effective computational methods to significantly reduce the number of computations. For their implementation there is a kind of function  $I[U_r^b(\Omega_0)]$  used, as well as functions  $U_r(\Omega_0, t)$ . The solution will be sought in the form of a piecewise constant function

$$U_r(\Omega_0, t) = \sum_{b=0}^N U_r^b \quad (r = 1, 2, \dots, m < n) \quad (7)$$

Let us consider the functional

$$I^* = \int_{\Omega_0}^{\Omega_k} [Q(\Omega, t) - Q^*(\Omega, t)]^2 + \int_0^t \int_{\Omega_0}^{\Omega_k} \sum_{i=1}^n F_i \left[ \frac{\partial Q_i}{\partial \Omega} \right] d\Omega dt \quad (8)$$

We shall put the integral (8) as follows:

$$I^* = \int_{\Omega_0}^{\Omega_k} [Q(\Omega, t) - Q^*(\Omega, t)]^2 + \sum_{b=0}^{N-1} \int_b^{t_{b+1}} \int_{\Omega_0}^{\Omega_k} \sum_{i=1}^n F_i \left[ \frac{\partial Q_i}{\partial \Omega} \right] d\Omega dt \quad (9)$$

The expression for the variation of Functional  $I^*$  can be written as follows:

$$\delta I^* = 2 \int_{\Omega_0}^{\Omega_k} [Q_1(\Omega, t) - Q^{*1}(\Omega, t)] \delta Q_1(\Omega, t) + \sum_{b=0}^{N-1} \int_b^{t_{b+1}} \int_{\Omega_0}^{\Omega_k} \sum_{i=1}^n F_i \left[ \sum_{s=1}^n F_s \frac{\partial f_i}{\partial Q_s} \delta Q_s - \frac{\partial f_i}{\partial Q_i} \right] d\Omega dt \quad (10)$$

By integrating the expression (10) part by part we obtain:

$$\delta I^* = 2 [Q_1(\Omega, t) - Q^{*1}(\Omega, t)] - c + \int_b^{t_{b+1}} F_r(\Omega_0, t) dt \quad (11)$$

The following condition should be satisfied:

$$2 [Q_1(\Omega, t) - Q^{*1}(\Omega, t)] = c$$

Then the formula (10) to express the variation is presented in the following form:

$$\delta I^* = \int_b^{t_{b+1}} F_r(\Omega_0, t) \delta U_r(t) dt \quad (12)$$

If functions  $Q^0(\Omega, t)$ ,  $F(\Omega, t)$  at arbitrary control  $U^0(t)$  satisfy the system (3), the increment of  $I$  under the influence of variation  $\delta U(t)$  of boundary control  $U(t)$  is calculated by the formula (12).

Let the variation of the functional  $\delta U(t)$  of boundary control  $U(t)$  have the following form:

$$\delta U(t) = \begin{cases} \text{const} & tb < t < tb + 1 \\ 0 & tb < 0 \text{ or } tb > t \end{cases}$$

Taking into account (12) we obtain the following formula to calculate the derivative:

$$\frac{\delta I}{\delta U_{rb}} = \lim_{\Delta U_{rb} \rightarrow 0} \frac{\Delta I}{\Delta U_{rb}} = \frac{\partial I}{\partial U_{rb}} = \int_b^{t_{b+1}} F_r(\Omega_0, t) dt \quad (13)$$

Or

$$\frac{\partial I(U_{rb})}{\partial U_{rb}} = \int_b^{t_{b+1}} F_r(\Omega_0, t) dt \quad (14)$$

Let us suppose that function  $F_r(\Omega, t)$  is continuous along  $\Omega$  and piecewise continuous along  $t$ . The required derivative  $\frac{\partial I(U_r^b)}{\partial U_r^b}$  for all

Nm derivatives can be defined by a piecewise constant function  $U(t)$  by solving a system of differential equations (3) with the boundary conditions (4) and carrying the  $Q(t)$  in sufficient number of points. Then it is necessary to solve the dual system:

$$\frac{\delta E_r}{\delta \Omega} = - \sum_{t=1}^n \frac{\delta f_i}{\delta Q_s} E_I \quad (s = 1, \dots, n) \quad (15)$$

To the system (3) with

$$E_s(\Omega, t) = 0 \quad (s = 1, 2, \dots, n) \quad (16)$$

$$E_1(\Omega, t) = c.$$

After that, the desired derivative  $\frac{\delta I}{\delta U_r^b}$  can be defined by the formula (14) in cross section  $\Omega = \Omega_0$ .

In other words, there is no need to solve system (3) Nm times and it is reduced solving this system and its conjugate system (15) just once with the boundary conditions (5) and (16).

Next, using the method of successive approximations it is necessary to solve the system at the next control impact by the formula:

$$U_r^{b,j+1} = U_r^b + \delta U_r^b rb \quad (17)$$

where:

$$\delta U_r^b < e \quad |e| > 0 \quad (r = 1, 2, \dots, m) \quad (b = 1, 2, \dots, N - 1)$$

In formula (17)  $j$  is a step of approximations.

If the original system solution (3) under the boundary conditions (4) is stable, it can be expected that when we integrate the adjoint system (15) with the boundary conditions (16) in the negative direction of the axes, its solution will also be stable and it does not cause computational difficulties, which sometimes can take place in nonlinear systems.

If there are restrictions for the control action parameters when the algorithm of calculating the optimum boundary program is made, it is necessary to meet the necessary requirements at each step:

$$U_r^{min} < U_r^{b,j+1}(t) < U_r^{max}.$$

### 3. Conclusion

The described method is used to derive the necessary and sufficient conditions for optimality of the boundary control of tape bearings. The optimality conditions are derived using indirect methods, by means of the direct satisfaction of optimality necessary conditions based on the classical variations calculus with application of Lagrange multipliers.

The authors suggested a method for calculating the boundary control in the tape bearings optimal program using the method of successive approximations. The calculation method is based on the solution of the so-called systems of coupled equations, taking into account the specifics of the boundary control and using a simplified algorithm for solving a quality boundary function.

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## CONCEPT OF DEVELOPING AN INTELLIGENT SYSTEM FOR CONTROL AND OPERATIONAL DIAGNOSTICS OF TECHNOLOGICAL EQUIPMENT CONDITION

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**Abstract.** The authors propose a concept for developing a system of automated monitoring and on-line diagnostics of main technological equipment conditions. Monitoring and diagnostics system should work along with the automated control system. In this case, the effects of the optimal control and operational forecasting of the process equipment will complement each other and enhance the overall efficiency of the system. The proposed technique for developing diagnostic algorithms with the use of intelligent technologies will speed up their development and improve the accuracy of forecasting.

**Keywords:** diagnostics, automated control system, intelligent system, algorithm, technological object

### KONCEPCJA BUDOWY INTELIGENTNEGO SYSTEMU KONTROLI I DIAGNOSTYKI OPERACYJNEJ STANU TECHNICZNEGO WYPOSAŻENIA

**Streszczenie.** Zaproponowano koncepcję budowy systemu automatycznej kontroli i diagnostyki operacyjnej stanu podstawowego wyposażenia technicznego. System kontroli i diagnostyki powinien działać razem z automatycznym systemem sterowania. Przy tym rezultaty optymalnego sterowania i operacyjnego prognozowania stanu technicznego będą dopełniać się wzajemnie i podwyższać całkowitą efektywność systemu. Proponowana metodyka zastosowania algorytmów diagnostyki z zastosowaniem sztucznej inteligencji znacznie przyspieszy ich opracowanie i podwyższy dokładność prognozy.

**Słowa kluczowe:** diagnostyka, automatyzowany system sterowania, system inteligentny, algorytm, obiekt technologiczny

#### 1. General information about technical diagnostics

Initially the maintenance of technological equipment (TE) to ensure its operational reliability and proper technical conditions was carried out “to failure” [2]. Since the second half of the last century another strategy, scheduled preventive maintenance (SPM), has been successfully applied. However, it becomes obvious that in the market conditions it is necessary to move to a more progressive approach of ensuring the operational reliability of TE, “in accordance with its actual condition” [2]. The transition to this strategy calls for the development of automated monitoring and on-line diagnostics system of TE technical condition (AMODS).

The use of assessment of TE systems in accordance with its actual condition allows improving the efficiency of production by reducing downtime under repair, bringing down production costs on account of reduction in expenditure on repair and post-fault reconditioning of equipment. (see Table 1) [2].

Table 1. Practical importance of AMODS application

Costs	Savings
Preliminary research, selection of monitoring points, definition of limit values. Developing a common database of equipment failures. AMODS development	Increase in average time between repairs (increased productivity and reduced maintenance costs). Actual elimination of unexpected failures (increased reliability and productivity). Elimination of excessive consumption of spare parts (replacement of defective parts). Reduction of the number of spare parts (providing warnings of the need to order replacement parts). Improved safety (reducing the likelihood of unforeseen failures). Increased productivity of production processes.

The costs of developing AMODS will be significantly reduced if included into the structure of existing automated process control system as a subsystem. In this case, an information application of the existing automated process control system will be used and this will greatly reduce the costs of its development and introduction. At the same time, the effect of the introduction of an advanced automated process control system will increase significantly because in addition to the effects of rapid and optimal process control the effect of rapid diagnostics of TE will be achieved (see Table 1).

Besides, there may be a so-called synergistic effect when the effects of the automated process control system and AMODS are not just added together but multiplied. It results from the mutual influence of process control and TE diagnostics: on the one hand prompt and optimum management of processes has a positive effect on TE, and on the other hand on-line diagnostics can save the condition of TE at the appropriate level, thus improving its controllability.

The AMODS diagnostic functions allow recording the beginning of destructive processes in TE at an early stage. These processes are irreversible, but their development can be monitored and predicted using the method of anticipatory multi-parameter diagnostics (MPD), which at each moment of time generates a complex estimate of monitored parameter trends. [11] The function of forecasting a condition classifies MPD as a proactive diagnostics, which can prevent undesirable developments in controlled equipment with control actions. Control actions include messages to operational staff on necessary actions and control signals for operating mode, up to disconnection of the OT in case of anticipation of destructive processes [11].

Existing methods of monitoring operational characteristics of TE consist in time-consuming periodic inspections of their values during planned supply disconnection performed by qualified personnel. These methods are considered test diagnostics. In case of invalid parameter values such control allows no possibility for timely prevention of reduction of TE operating resources. At the same time, a system of continuous computer monitoring can monitor the rate of TE performance change, predict the time of necessary repairs to extend its safe operation and to prevent the inevitable failure of equipment.

Thus, the combined operation of automated process control system and AMODS can manage processes not only efficiently and optimally, but also safely for TE.

One of the important stages of AMODS development is determining diagnostic features, whose amount and information content should be taken into account in accordance with specifications accepted at the stage of design and installation, performance of prototype objects, and special features of the operating conditions of diagnosed objects. [2]

Diagnostic feature (DF) is an attribute of an object of diagnostics used in accordance with the established procedure for determining the condition of an object. Each type of system of a certain type can be specified as a variety of attributes that

characterize its condition. In accordance with their intended purpose, most of DFs can be both diagnostic and attributes of functional use. It is these attributes, that can often be measured directly, and are easier to establish standards and limits. Going beyond such limits indicates a failure or a defect in the functioning of a system [2].

Regularities of changes in DFs over time are generally similar to the regularities of parameter changes of object technical condition. During operation DFs vary from their initial value to the maximum allowable for a certain operating period. By measuring the current value of a DF and comparing it with the attributes of the reference condition of an object, one can determine a technical condition of the object at this moment and predict its subsequent condition. The assortment of DFs and the permissible limits are established by manufacturers and are specified in the technical documentation. Typically, a diagnostic conclusion requires an analysis of a large number of DFs [11].

In general, development of AMODS requires solving the following interrelated tasks:

- to develop a mathematical model of an object under diagnostics, which allows to check working capacity and correctness of functioning on the strength of all the DFs.
- to create a mathematical model of damages and failures, which gives an opportunity to detect damages and failures and identify their causes.
- to build algorithms for diagnostics, which is achieved by selecting a set of elementary inspections to help: a) in the problems of detecting damages and failures to distinguish serviceable or working condition or condition of the proper functioning from its faulty conditions; b) in the problems of looking for damage and failures to distinguish between faulty and inefficient conditions [11].

For solving these problems various mathematical models are used. For example, when creating models which allow testing the functionality and correctness of functioning we use systems of linear and nonlinear equations. For modeling of damages and failures we use topological models in the form of fault trees and graphs of cause-and-effect relationships between the technical conditions and DFs. The models of objects under diagnostics are the basis for constructing algorithms for diagnostics. Construction of diagnostics algorithms consists in selecting of such sets of inspections whose results can distinguish serviceable condition, working condition or condition of the functioning from their opposite conditions, and also to distinguish types of defects between each other [11].

A state of a system is described by a set of features defining it (parameters). Of course, the multitude of defining attributes may vary, especially in connection with the recognition problem. Recognizing conditions of a system means referring it to one of possible diagnoses (classes). The number of diagnoses depends on the objectives and purposes of study [2].

In the majority of problems of technical diagnostics, diagnoses are established in advance, and in these conditions the recognition problem is often called the problem of classification. A set of sequential actions in the recognition process is called a pattern recognition algorithm. An essential part of the recognition process is the selection of diagnosing features (DF) that describe the condition of the system. They should be informative enough to allow the recognition process to be carried out under a selected number of diagnoses. With the collection of statistical data, the list of DFs should refine and improve the decisive rules for recognition of defects [1].

There are two main approaches to the problem of recognition, probabilistic and deterministic. Probabilistic methods require a large amount of background information. Deterministic approaches more succinctly describe the essential aspects of the recognition process, are less dependent on excessive, low-value information, are more in line with the logic of human thinking. However, the deterministic approach requires knowledge of qualitative and quantitative regularities of physical and chemical phenomena going on in the TE, which is not always

possible. One of the most important features of the technical diagnostics is to detect faults in the condition of limited information when one needs to be guided by certain principles and rules to make an informed decision.

In these circumstances, the most promising approach may be to use a modern intelligent technology (IT) for problems of pattern recognition. At present the most commonly used in practice ITs are: fuzzy logic, neural networks and neuro-fuzzy network. In our reference [6] we proposed a method for the application of intelligent technology to develop technological process control systems. However, we believe that this technique can be applied to creating systems of diagnostics of process equipment, since the study, development and implementation of processes of technical condition of the diagnosis are necessary to solve the same problems that arise in the research, development and implementation of management processes in general [4].

## 2. The method of application of intelligent technologies in control systems

The Department of Automation and Controls of K. I. Satpayev KazNTU is actively engaged in research and development of hybrid and intelligent control systems of various technological processes, such as [4, 5, 6, 8, 9]. Numerous studies conducted at the department, as well as analysis of recent publications on the subject have shown that IT can be used directly in the development of models for optimal process control, but not a model of the process itself. In other words, the considered technologies enable the immediate development of control algorithms, as opposed to the traditional chain: development of a structure of process model → conducting experimental studies on the object → model identification → optimization problem formulation → selection of optimization method → optimal control algorithm development. The traditional approach involves a long (sometimes several years), expensive and not always successful way of creating a system of optimal control.

The use of IT allows solving analogous problems immediately, and as experience has shown, quite successfully. The fact is that artificial intelligence techniques involve the use of knowledge, experience and intuition of human experts who are familiar with the subject area. In other words, it uses the so-called effect of "ready-made knowledge." In contrast, the development of a mathematical model (the main component of the system) is the process of creating "new knowledge", and therefore requires a long enough time to conduct theoretical research, as well as high material and labor costs for pilot studies and model identification.

Moreover, thanks to their long-term work experience, operators-technicians have learned how to control technological processes in optimized modes in different initial situations (and they usually manage to perform well). The transfer of "ready knowledge" from human experts to the knowledge database of an intelligent system greatly simplifies the development of intelligent systems; and their operation eliminates the effect of the "human factor" during process control (under "human factor" we assume such properties of a human body as: fatigue, slow reaction, lack of psychological stability, drowsiness during monotonous work, limited experience of young operators, and other causes).

Using the main idea of work (instead of development of a technological process model, development of a model of its control process), and developing existing IT methods, we propose the following three stage process of creating systems of optimum process control.

At the *first stage*, a priori studies of technological features of the control object based on literature sources, publications in periodicals and production forms and records are carried out. Typically, existing processes have to go through a long phase of research, pilot and industrial tests before they are put into production. It is likely that there remained materials of this research, as well as attempts to develop mathematical models of this process. A thorough analysis of all this information in order

to use it in the development of intelligent control systems is required. This is especially important for the possible creation of hybrid control systems (HCS).

At the same stage it is required to analyze the process under study as a control object with the identification of input and output, controlled and uncontrolled, manageable and non-manageable variables. It is necessary to assess the object response rate through different channels, the class of object (continuous or discrete), the degree of completeness of the information about the object's variables, the operating range of variation of variables of the object, etc.

After careful analysis of the available information it is necessary to prepare a structure of the future system of control, which will considerably facilitate further work.

At the *second stage* the model of control process is developed. The main objective of control (analogue of objective function in optimization problems) is determined with the help of experienced experts (practicing operators, technicians or engineers). This objective is generally known and usually experienced operators are striving to achieve it. Then of all types of variables by the method of ranking from the general list are defined those which according to experts are essential to this object (process).

The main objective of the second stage is the compilation of a matrix of planning a full factorial experiment (FFE). A model of a control object (process) is made with the help of a FFE matrix. At the same time, for example, the total number of possible combinations of factors for two input variables for three-level factors is equal to  $N=3^2=9$ ; for three variables  $3^3 = 27$ , etc.

For example, when there are two input variables, a FFE planning matrix is compiled, which is given in Table 2. Type 2 tables are the foundation for the development of intelligent systems, as they have concentrated many years of experience, knowledge and intuition of human experts in the particular subject area. The quality of the FFE matrix will depend upon efficiency of the entire control system.

The values: 0.0, 0.5, 1.0 mean the minimum, average and maximum values of the input variables  $X_1$  and  $X_2$ . An expert using his experience, knowledge and intuition has to only write down the values of the output variable  $Y^o$  (controlling action) in the range from 0.0 to 1.0. Normalization in the range from 0 to 1 of input and output variables is done according to the formula:

$$\bar{x} = \frac{x - x_{\min}}{x_{\max} - x_{\min}}, \quad (1)$$

where:  $\bar{x}$  - normalized (from 0 to 1) value of an input or an output variable;  $x$  - current value of the variable;  $x_{\min}, x_{\max}$  - minimum and maximum value of the variable.

Table 2. FFE Matrix of Planning

Experiment number	X1	X2
1	0,0	0,0
2	0,0	0,5
3	0,0	1,0
4	0,5	0,0
5	0,5	0,5
6	0,5	1,0
7	1,0	0,0
8	1,0	0,5
9	1,0	1,0

Drawing up a matrix of experiment planning is much more convenient for experts than making rules of fuzzy productions recommended in all textbooks and publications. At that, an expert needn't invent endless terms ("very much", "very, very little," "quite normal", etc.); he just puts the value of the output (controlling) variable in the range from 0.0 to 1.0. In this case, the FFE matrix of planning can be used for four different methods of control model development: experiment planning, expert systems, neural networks, neuro-fuzzy algorithms.

In contrast to the well-known classical method of experiment planning, compiling a matrix of FFE planning with the help of experts makes this procedure considerably faster and cheaper. Experts carry out so-called "mental experiments" instead of expensive experiments conducted in reality. Besides, it is necessary to keep in mind that active experiments in the conditions of a functioning production process is unrealistic because of the possible emergency situations when the process variables fluctuate from the minimum values to their maximum values, and vice versa. In addition, many enterprises simply do not have opportunities to change the variables according to the FFE Planning Matrix.

It should be emphasized that the output values  $Y_i$  are actually control variables, so the planning matrix displays a process control model for all scheduled by experts combinations of input variables. For calculation of intermediate values in combinations of input variables (for example,  $X_1 = 0.21$  and  $X_2 = 0.74$ ) it is necessary to synthesize a process control model, which is the main task of the second stage.

It should be noted that it is more efficient to use known mathematical relationships identified in the first stage of research along with intelligent models. At the same time, it is necessary to make sure that such dependencies adequately reflect certain physico-chemical regularities of a particular process.

At the *third stage* a study of developed control models is conducted. At this stage the following actions are carried out.

The received models are thoroughly researched and analyzed by their sensitivity, stability and uniqueness. This is achieved by conducting a simulation of a control process with various changes of input variables; constructing the curves of variation of output variables at changing input variables; and performing their analysis with the help of experts.

After completion of investigation of models obtained by different methods, the comparative analysis of their adequacy is carried out. For this purpose the output variables are calculated using models for the values of input variables taken from the FFE planning matrix and compared with the expert estimates. After that a comparison matrix is formed, which allows to calculate the value of modeling errors in different ways. For example, the absolute error in percentage is calculated as follows:

$$\delta = 100 \frac{1}{N-1} \sum_{i=1}^N |Y^o - Y^p| \cdot \quad (2)$$

where  $Y^o$  and  $Y^p$  are experimental and calculated values of the output variables respectively.

An absolute error is calculated for the models obtained in four different ways, and then their comparative analysis is performed. The model with the smallest absolute error is considered to be the most appropriate.

The most adequate model is subject to taking tests in simulated conditions of existing production. In this case, the model is fed to the input with actual input variables taken from the measuring apparatus of an industrial unit; and the simulation results (output control variable) are compared with the value of control, which is effectively implemented by an experienced operator-technologist. In case of a satisfactory result of simulation tests, the model is integrated into an industrial controller. Otherwise, everything starts over again – going back to the first stage and improvement of the model parameters.

### 3. Technique of development of intelligent diagnostics algorithms

As it was already mentioned, the above suggested technique of application of intelligent technologies for development of process control systems can be used for TE fault detection tasks. Let us consider the use of intelligent technologies using the example of FFE planning matrix for TE fault identification providing the production of yellow phosphorus in the conditions of Novo-Dzhambulsky Phosphorus Plant (NDPP).

The NDPP technological instructions for the production of yellow phosphorus contains a lot of options for possible

malfunction of the TE and considers the ways of their elimination. Let us look at some of them (see Table 3).

There are three different conditions of a technical system [10]:

- 1) Workable – it is a condition under which the system is able to perform specified functions with parameters, which are set up by technical documentation.
- 2) Workable, but faulty – it is a condition of a technical system when it is able to perform its main functions, but does not meet all the requirements of technical documentation.
- 3) Failure – violation of system operation capacity, i.e. a condition when it is unable to perform specified functions.

Table 3. Possible malfunctions and methods of their liquidation

No	Type or symptom of malfunction	Possible causes of malfunctions	Actions of the personnel and ways of malfunction liquidation
...	...	...	...
5	Increase of temperature under the cover of electric furnace	1. Stuck of the charge in the boot chutes 2. Overexposing slag 3. Short electrodes 4. Excess of coke in the charge 5. Burner of an electrode	1. Identify the chute with a frozen charge and "break" it in accordance with instructions 2. Drain the slag with a maximum removal of coke 3. Switch on electrodes again 4. Flush with coke-lean charge 5. Act by orders of the shop technologist
6	Temperature under the cover of furnace is below the limit	1. High content of P <sub>2</sub> O <sub>5</sub> in the slag 2. Low power of electric furnace	1. Adjust furnace charge 2. If possible, increase power. In case of need close sectoral chute closures without violating the uniform dynamic load of charge on electrodes
...	...	...	...
10	Lowering the water level in the tank of "softened" water	1. Water leakage due to burn-out of one or more cooling elements	1. Turn off the electric furnace 2. Determine the location of burnout and replace or block the element
...	...	...	...

According to this classification the malfunction Number 6, is likely to be attributed to the second group of conditions of technical systems – “workable, but faulty.” Problem Number 10 can be attributed to the third group – “failure”. Problem Number 5 is closest to the group of failure, but it has some features of the second group.

The most dangerous for TE are certainly failures. Therefore we shall consider the third group of the technical system conditions in greater detail. Failure is the core concept of the theory of reliability. A failure occurs a result of action on an object by a set of objective and subjective factors. These factors are quite difficult to be fully taken into account [10].

#### Classification of failures:

1. Failures are distinguished by causes as:
  - *Constructional*, caused by deficiencies in design;
  - *Technological*, caused by imperfections or violation of manufacturing technology;
  - *Operational*, caused by improper operation.
2. Failures are distinguished by effect on the performance of a technical system as:
  - *Failures* of elements of the system, causing its malfunction;
  - *Failures of elements* of the system, causing its failure.
3. By relations with the failures of other elements:
  - *Dependent failures*;
  - *Independent failures*.
4. By randomness of occurrence:
  - *Random (sudden)*;
  - *Gradual (systematic)*.

Of course, the classification proposed in [10] (as well as any classification) is conditional as sometimes the problem can be attributed to several of its kinds. For example, the malfunction Number 5 can be attributed both to a group of “failures” and the

group “workable, but faulty”; it may be caused by structural as well as operational reasons, and it can occur either suddenly or gradually.

It should also be noted that all of the above problems are of “emergency notification” nature, i.e., they inform that an emergency situation has arisen, but do not allow to predict it. Qualitative (not quantitative) assessment of symptoms and causes of malfunction, do not enable “predicting” the proximity to a particular emergency situation. To forecast it (as noted in all the textbooks on technical diagnostics, as well as by the authors [11]) it is necessary to develop a mathematical model of object diagnostics, a mathematical model of damage and failures, and to build algorithms for diagnostics.

However (as already noted in paragraph 2 of this paper), this approach assumes a long, expensive and not always successful way of developing a system of on-line diagnostics. We use the same method as for developing control systems: i.e. instead of creating mathematical models of diagnostics objects and failure models we immediately begin developing an algorithm for diagnostics using advanced intelligent technologies. The use of IT can solve similar tasks at once, and as experience has shown (e.g., [4, 5, 6, 8, 9]), quite successfully. In other words, the effect of “ready knowledge” derived from human experts would be used in this case.

The basis of the proposed methodology for diagnostics algorithm development is composed by (see Section 2 of this paper) FFE planning matrix instead of the traditional rules of productions. Let us consider the method of producing the FFE planning matrix using the example of diagnosing the problem Number 5.

The fluctuation of temperature in a furnace is quite a “standard” situation, which is controlled by raising or deepening electrodes – “fine adjustment”, or switching steps of a transformer – “rough adjustment” explained by the divergence of chemical and physical properties of the loaded charge. However if the temperature exceeds a certain threshold level, and it cannot be reduced by the control system, it means the occurrence of an emergency situation according to the above-mentioned five reasons. In other words it is possible to say that if the change in temperature is compensated to a certain extent by a control action, the technical condition of the furnace is considered normal within the region of the control system (AMODS). At the same time, even if the temperature is still within the limits, but is not governed by the control system that gives a command to lower it, it means that the situation is close to an emergency and it is necessary to move into the sphere of influence of the diagnostics subsystem - AMODS.

In the work [7], we attempted to assess the quality of a newly developed technical system by evaluating its controllability. Here we can use the same criteria for evaluation of the current technical system from the point of view of TE current condition. In other words, we used the current rate of controllability of process equipment as a diagnostic feature (DF). This can be done in the presence of an automated process control system, which allows monitoring and evaluating the effect of input, output and control variables on TE.

Thus, determining the degree of TE controllability allows to evaluate the possibility of occurrence of emergency situations at an early stage. In accordance with the definition of Kalman [3], controllability (elimination of initial displacement) means the ability of a system to have control actions that allow to transfer it from a given initial condition to a desired one within a limited period of time. In the work [7] a profound analysis of numerous methods for determining the controllability of TE is provided, but they are quite complex and require knowledge of the static and dynamic characteristics of the controlled object, which is not always possible. In the work [7] we provided a methodology to assess the degree of controllability of TE which uses knowledge, experience and intuition of operators-technologists along the advanced intelligent technologies.

To determine the degree of current controllability of TE it is suggested to use the following criteria: static evaluation of control channels, assessment of TE inertia, interference immunity, and measurability. Since the criteria for interference immunity measurability of TE change much over the time, they cannot be considered in assessing the overall controllability of TE.

As an example, let us consider a methodology for assessing a degree of controllability of TE for the malfunction Number 5.

In this case, for the static assessment we take the following variables:

- temperature under the electric furnace cover ( $X_1$ );
- value of penetration of electrodes ( $X_2$ );
- switching transformer steps since the beginning of temperature increase ( $X_3$ ).

As dynamic estimates we assume the following parameters:

- speed of temperature increase ( $X_4$ );
- inertia of the object ( $X_5$ ) along the channel “depth of immersion of electrode - temperature in the furnace”, this is a reaction time of TE (furnace temperature) for controlling impact (depth of immersion of the electrode).

As an output variable we will assume the overall assessment of controllability ( $Y$ ).

All of these variables (except for the transformer changing steps) can be normalized using the formula (1), which allows to estimate their values change from minimum to maximum in the range [0 - 1].  $X_3$  variable can have only two values: 1 (there was switching of steps) and 0 (there was no switching of steps).

One should also consider that almost all the criteria and the evaluation of the static and dynamic control channel will vary depending on the furnace capacity. It is therefore necessary to form the FFE planning matrix for each value of power  $W_i$  separately.

We can now proceed to the main point – the compilation of production rules or the formation of a knowledge base of experienced on-site operators-technicians or engineers for production of yellow phosphorus at NDPP. For example, the rules may be:

**Rule 1:** “IF THE TEMPERATURE IS MINIMAL” AND “THE IMMERSION IS MINIMUM” AND “THERE WAS NO SWITCHING” AND “THE RATE OF TEMPERATURE INCREASE IS MINIMAL” AND “THE INERTIA OF OBJECT IS LOW” THEN “THE CONTROLLABILITY IS HIGH”;

**Rule 2:** “IF THE TEMPERATURE IS MAXIMAL” AND “THE IMMERSION IS MAXIMAL” AND “THERE WAS SWITCHING” AND “THE RATE OF TEMPERATURE INCREASE IS MAXIMAL” AND “THE INERTIA OF OBJECT IS HIGH” THEN “THE CONTROLLABILITY IS LOW”;

**Rule 3:** “IF THE TEMPERATURE IS MEDIUM” AND “THE IMMERSION IS MEDIUM” AND “THERE WAS NO SWITCHING” AND “THE RATE OF TEMPERATURE INCREASE IS MEDIUM” AND “THE INERTIA OF OBJECT IS MEDIUM” THEN “THE CONTROLLABILITY IS MEDIUM”;

etc.

It is more convenient to present these production rules in a form of FFE planning matrix after conducting so-called “mental experiments” with experts. Then the planning matrix for these three rules will look as follows (see Table 4).

Table 4. FFE planning matrix+ for the assessment of controllability for  $W_i$  power

Experiment No.	$X_1$	$X_2$	$X_3$	$X_4$	$X_5$	$Y$
1	0	0	0	0	0	1
2	1	1	1	1	1	0
3	0.5	0.5	0	0.5	0.5	0.5

To ensure a full factorial experiment with a three-level assessment of variables: 0; 0.5; and 1.0, the number of experimental points will be equal to:  $N = 3^5 = 153$ . But it is desirable to apply a five-level assessment: 0.0; 0.25; 0.5; 0.75; and 1.0; while the number of points will be equal to  $N = 5^5 = 2625$ . However, this large number of experiments is difficult to implement. In this case one can perform fractional factorial experiment (FrFE) with fewer experimental points [4]. It should be remembered that the accuracy of intelligent models for control systems should be much higher than for a diagnostic subsystem. Therefore, the number of points in FrFE for the diagnostic system can be significantly fewer than that required for the furnace control. But in any case, the more “mental experiments” will be conducted, the more accurate the mental model of the algorithm of diagnosis will be.

The FFE planning matrix can be used for the synthesis of one of the three types of intellectual models: fuzzy, neural network or neuro-fuzzy. There are further studies into the sensitivity, stability, unambiguousness and adequacy of received intellectual models. The best of these three models may be used in developing the AMODS diagnostic subsystem.

Further it is possible to adopt, for example, the following evaluation grading for the degree of closeness of the current condition of TE to the emergency situation (for malfunction Number 5) depending on the evaluation of the degree of controllability:

- a) if the value  $Y$  is between 0 and 0.25 – the emergency situation occurred;
- b) if the value  $Y$  is in the range from 0.26 to 0.5 – the situation is prior to emergency;
- c) if the value  $Y$  is in the range from 0.51 to 0.75 – the emergency situation is likely;
- d) if the value  $Y$  is in the range from 0.76 to 1.0 – the furnace is in the normal condition.

Depending on the assessment of the degree of furnace controllability, AMODS can make one of the following decisions:

- in the case (d) – no action to be taken;
- in the case (c) – analyzing possible reasons for the decline of controllability: bridging scaffolding in boot chutes; overexposure of slag; short electrodes, excess of coke in the charge; bummer of electrode;
- in the case (b) – depending on the results of analysis making one of the following: identifying the chute with a frozen charge and “breaking” it according to instructions, draining the slag with a maximum removal of coke; switching electrodes on again or providing “flushing” with coke lean charge;
- in the case (a) – acting by the orders of an on-site technologist.

Similarly, one can develop a FFE planning matrix and assess the degree of controllability during the furnace malfunction Number 6. Malfunction Number 10 by this classification [10] can be classified as random (sudden), the causes of which are impossible to predict in advance. The malfunctions of this type are recorded with appropriate sensors, and the reaction to them is stipulated in the technological instructions and can be duplicated on a monitor using an AMODS subsystem.

Thus, the proposed method of estimating the degree of controllability allows predicting the occurrence of accidents at an early stage and preventing them.

#### 4. Conclusions

The original methodology for the development of real-time diagnostics intellectual algorithms on the basis of evaluation of process object control level is proposed. This methodology provides application of knowledge, experience and intuitions of technologist operators, given in the form of the planning matrix of Complete Factorial Experiment (CFE). At that the CFE planning matrix is planned by experienced technologist operators in the mode of “mental experiment”, thus significantly saving labor costs and material resources.

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## AUTOMATED NMR-RELAXOMETRY FOR CONTROL OF PRODUCTION AND QUALITY

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**Abstract.** In this work we show the possibility of using of nuclear magnetic resonance at low magnetic fields for the purpose of establishing a system of automated process of control and quality of dairy products.

**Keywords:** nuclear magnetic resonance (NMR), relaxometry, chemical shift, automated control system

### AUTOMATYCZNY RELAKSOMETR NMR DO KONTROLI PRODUKCJI I JAKOŚCI

**Streszczenie.** W pracy przedstawiono możliwość użycia jądrowego rezonansu magnetycznego dla słabych pól magnetycznych do stworzenia zautomatyzowanego systemu kontroli procesu i jakości produktów mlecznych.

**Słowa kluczowe:** jądrowy rezonans magnetyczny, relaksometr, przesunięcie chemiczne, zautomatyzowany system kontroli

### Introduction

There are various methods to control the quality of products based on the use of various physical and chemical effects. This paper describes the possibility of using NMR spectroscopy for the purposes of automated quality control of milk using a magnetic field. By studying the NMR spectra of isotopes that are part of the milk, you can unambiguously identify the product, in other words to determine its authenticity.

### 1. Method and equipment of NMR spectroscopy

The use of NMR spectroscopy is well known for controlling the manufacturing process [1].

Under the influence of an external magnetic field, atomic nuclei can receive and emit radio waves. Their frequency  $v_0$  is proportional to the strength  $B_0$  of the magnetic field:

$$\omega = 2\pi v_0 = \gamma B_0 \quad (1)$$

here, the coefficient of proportionality is the gyromagnetic ratio  $\gamma$ . It is a constant value for a particular nuclear isotope.

The content of certain isotopes in the nature and the corresponding frequencies of the radiation are given below:

Table 1. Properties of several atomic nuclei

Nuclear isotopes	Content in the nature	$v_0$ at $B_0 = 1$ T
<sup>1</sup> H	99,98%	42,57 MHz
<sup>13</sup> C	1,108%	10,71 MHz
<sup>14</sup> N	99,63%	3,08 MHz
<sup>19</sup> F	100,0%	40,05 MHz
<sup>129</sup> Xe	26,44%	11,78 MHz

Nuclear magnetic resonance (NMR) is a peculiar form of telecommunications in the magnetic field, because the NMR frequency determined by the value of the magnetic field at the point where the core is. Atomic nuclei are surrounded by electrons and in the compounds, which are formed by different atoms

i.e. molecules, electrons can be shared, forming a chemical bond. The orbits of binder electrons are characteristic of the chemical structure of molecules. As is well known electrons carry an electrical charge, movement of which induces a magnetic

field. The internal magnetic field induced by electrons that are moving in an external magnetic field  $B_0$ , is usually proportional to this field and shields the nucleus from it.

The induced magnetic field causes a shift of the resonant frequency:

$$\omega_L = 2\pi v_L = \gamma(1 - \sigma)B_0 \quad (2)$$

where  $\sigma$  is a constant of magnetic shielding for a given chemical group.

Value of  $\delta = (v_L - v_{ref})/v_{ref}$  is the chemical shift of this group. It does not depend on the strength of the magnetic field  $B_0$ . Chemical shifts can be calculated from the chemical shift increment tables, as well as on the basis of the laws of quantum mechanics. Value of  $v_{ref}$  is a reference frequency, for example, the resonant frequency of tetramethylsilane (TMS) for <sup>1</sup>H and <sup>13</sup>C. In liquids the resonance signal typically has a width of 0,1 Hz.

The distribution of the resonance frequencies defines the NMR spectrum, which displays the structure of the molecule. On the Figure 1 NMR spectrum is shown <sup>13</sup>C in polyethylene. Identification of NMR spectrum of molecules in solutions is a standard method of analysis for the further chemical synthesis and accordingly the quality of a particular type of the manufactured products.

In recent years the NMR is widely used for control and management of various technological processes, for example, in the manufacture of medical preparations in the pharmaceutical manufacturing [9], for monitoring the quality of agricultural products [2, 3, 5, 6].

It is known that applicable in spectrometers permanent magnets depends on the temperature. Nevertheless, such spectrometers which measure the echo or signal induced in the coil after the initiation of the pulse – is a free induction decay (FID) in weakly inhomogeneous fields are widely used for characterizing a variety of types of products, for example, foods, cosmetics, polymers. FID frequency analysis in using Fourier transformation gives you the opportunity of obtaining NMR spectrum with linewidth

$$\Delta\Omega = 1/(\pi T_2) \quad (3)$$

where  $T_2$  is the transverse relaxation time, which is determined by local magnetic fields dependent or independent of the time. With the proper conduct of the experiment the accuracy of such measurements is 0,1%.

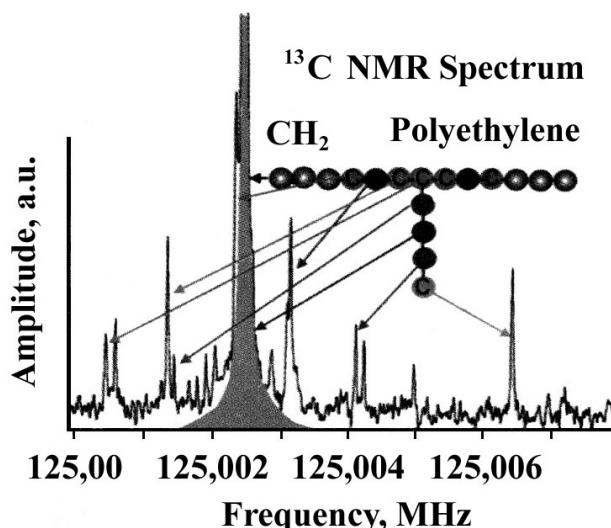


Fig. 1. Chemical structure

NMR with a weak field can be reproduced with the help of a small and low-cost equipment, value of which can be obtained in the range from 0,5 to 1 T by using electromagnets. NMR with a weak field in the homogenous fields can be used to control the manufacturing process, for example, petroleum refining or other types of products, for example the quality of milk. For optimizing the product stream after the spectrometric analysis the return signal is generated from the parameter  $^1\text{H}$  of NMR spectrum.

## 2. Description of the automated system for determining the quality of milk

This paper considers the automatic control system (ACS) of the milk quality when it is processing by the magnetic field. In recent years, paid much attention to the processing by physical fields of liquids [7, 8, 10].

We have attempted to use the magnetic field for milk processing with a view to its better storage. For controlling parameters of quality of milk have developed an automated control system (ACS), which is regulated by the seven parameters (fat mass fraction, the mass fraction of milk solids non-fat (MSNF), the density, the mass fraction of added water, the temperature, the mass fraction of protein, the acidity). Moreover for controlling the magnetic field with a high accuracy NMR signal of hydrogen applied  $^1\text{H}$  and of carbon  $^{13}\text{C}$ , which by the chemical shift indicate the presence of microbial flora in the milk.

A block diagram of the device shown at the Figure 2. Milk from the reservoir via delivery pipe (1) supplied to the sliding shutter (2), which regulates the velocity of the fluid. Next, the milk supplied to a system for electromagnetic treatment of milk (3), consisting of several pairs of quadrupole lenses (EM-1, EM-2 etc.), which have a special configuration of the magnetic tips. Value of the magnetic field strength is measured with a high accuracy up to  $10^{-5}$  by an NMR sensor (4), which is in the area of fields of the quadrupole lenses.

The parameters of milk (as input (7), and output (8)) are controlled by sensor devices, installed in the analyzers «Laktan-4», «AKM-98 Farmer». They allow to register up to 6 parameters of milk quality.

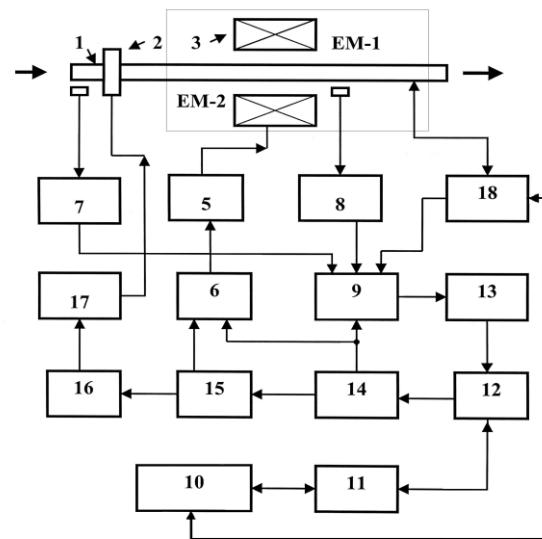


Fig. 2. The block diagram of the ACS: 1 – delivery pipe; 2 – sliding shutter; 3 – device for electromagnetic treatment of milk; 4 – NMR sensor; 5 – power amplifier; 6 – digital-to-analog converter (DAC); 7 – input sensors of properties of milk; 8 – output sensors of properties of milk; 9 – controlling signal switch; 10 – personal computer; 11 – LPT-port; 12 – interface; 13 – registrar of receiver; 14 – registrar of control; 15 – data recorder; 16 – switch of the stepper motor; 17 – stepper motor; 18 – NMR spectrometer

Input and output data from the sensors are supplied to the controlling signals switch (9) through the appropriate interface and LPT-port (11) to the personal computer (10). In the personal computer, there is a required software, designed to control the strength of the magnetic field of quadrupole lenses. The magnetic field is generated by electromagnets, supplied and controlled by a DC voltage source (5), control signals from the PC via the digital-to-analog converter (DAC) (6).

The second branch of the adjustment of the fluid velocity is given through the registrar switch management of the stepper motor with the corresponding electronic equipment, given at the Figure 1. Milk flow rate through the delivery pipe can be adjusted in the range from 0 to 6 m/s. with accuracy of 0,15%.

In the present paper uses the method of analysis of the asymptotic stability developed and [1] designed to obtain frequency stability conditions of subsystems of direct digital control of regime parameters of considered technological processes.

## 3. Identified results

We have experimentally determined, magnetic treatment of milk for field strengths up to 0,5 T reduces the deposition of salts and the formation of milk stone up to 3 times, which contributes to lower heat and power costs, prime cost of dairy products, their quality improvement. Magnetized milk has a higher viscosity (up to 16-18%), critical shear stress of milk coagulum (up to 23-28%), electrical conductivity (up to 14-16%), the surface tension of the milk is reduced up to 11-15%.

An important indicator for establishing the expiration date is the acidity.

Titratable acidity is a key indicator of freshness of milk and dairy products. It reflects the concentration of milk components having acidic character. It is known that the active acidity is one of the indicators of quality, it is determined by the concentration of hydrogen ions. On the pH value depends the colloidal state of the milk proteins, growth of beneficial and harmful microflora, thermostability of milk and activity of the enzymes.

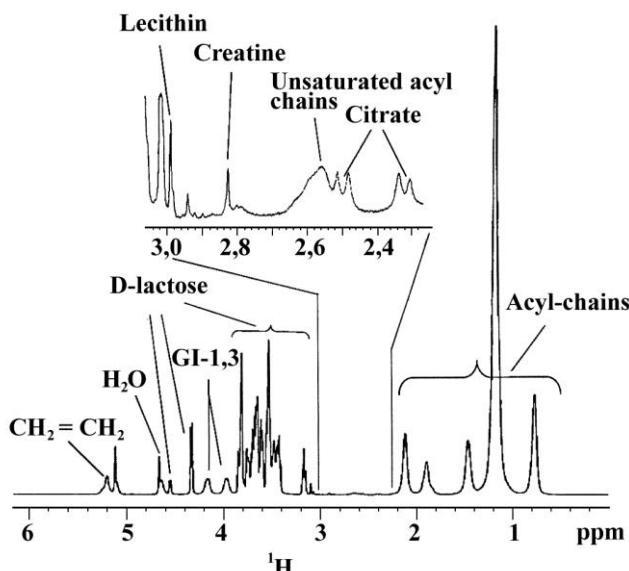


Fig. 3. <sup>1</sup>H NMR spectrum of milk

Thus, a constant magnetic field is a biologically active factor of the external environment that may affect to the liquid systems and bacteria.

Great interest attaches the NMR technique of determining the chemical shift of the hydrogen, carbon, phosphorus, which characterize the nuclear-physical parameters of milk.

As an example, Figure 3 shows a portion of the NMR spectrum signal of milk for hydrogen-1 isotope.

#### 4. Conclusions

This paper shows the feasibility of establishing a system of automated quality control of liquid milk using NMR, having a high accuracy of determination of manufactured products.

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## QUALITY MANAGEMENT SYSTEM IN HEAT SUPPLY OPERATION

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**Abstract.** In the article, the Quality Management System (QMS) in heat supply is shown as a high-quality and reliable heat supply ensuring system for consumers (in the most cost-efficient way compliant with environmental standards) and ensuring the quality assessment of functioning business. The article provides features of heat supply, as control object, and difficulties of assessing the quality of functioning business. It also provides a process approach to description and management of activity, as one of management principles in QMS.

**Keywords:** management of district heating, the hierarchical system, the system of management and quality

## SYSTEM ZARZĄDZANIA JAKOŚCIĄ W DOSTARCZaniu CIEPŁA

**Streszczenie.** W artykule system zarządzania jakością w dostarczaniu ciepła potraktowano jako system zapewniający wysoką jakość i niezawodność dostarczania ciepła klientom w najbardziej ekonomiczny sposób, przy jednoczesnym zapewnieniu standardów ekologicznych i uwzględnieniu oceny jakości funkcjonowania przedsiębiorstwa. Wskazano cechy szczególne dostarczania ciepła jako obiektu sterowania oraz trudności w ocenie jakości funkcjonowania przedsiębiorstwa. Przyjęto podejście procesowe do opisu i sterowania dostarczaniem ciepła jako zasady sterowania systemem zarządzania jakością.

**Słowa kluczowe:** zarządzanie dostarczaniem ciepła, system hierarchiczny, system zarządzania jakością

### Introduction

Currently, many enterprises to improve the performance and competitiveness of the domestic and global markets are implementing the Quality Management System. How does the introduction of this system in a centralized heating system will affect the quality and reliability of supply, whether it will increase energy efficiency, in accordance with environmental standards? Allow to achieve this goal, and to assess the quality of operation of the business. These and other questions will try to answer in this article.

### 1. Features heating as a control object

Contemporary district heating systems (DHS) of cities correspond to complex technological systems consisting of basic interrelated district-heating processes (CHP and auxiliary boiler rooms), main and sub-main heating utilities (HU), and spatially distributed network of heat and domestic hot water (DHW) consumers.

Operation of DHS shall be in compliance with technical requirements to hydraulic/thermal modes and to reliability of components – regarding the technical-economic indicators of heat supply [7].

As the target of research and control, HS is characterized by [4]:

1. Complex interrelationships between heating, domestic hot water, and ventilation processes;
2. External links to other facilities (water supply and CHP);
3. Continuity in production, distribution, and consumption of thermal energy;
4. Dependent and independent schemes of connecting the thermal energy consumers to heat-supply system;
5. Non-stationary nature of hydraulic and thermal heat-supply modes;
6. Stochastic nature of disturbances;
7. Problems in assessing the current values of technical-economic indicators (process management quality);
8. Spatial distribution of heating facilities;
9. Increased sensitivity of heat carrier to water leaks and accidents – in areas and nodes of heating utilities;
10. High-density of heat carrier, which requires additional power costs for network water pumping and arrangement of high pressure – to fill the heating elements of consumers.

Activities of heat-supply plant are estimated by the following components [8]:

- quality of maintaining the technical status of heating utilities;
- modal reliability;
- quality of remediation activities;
- quality of building and replacing the heating systems;
- reliability management at the enterprise.

### 2. Quality management system in management heat supply

In practice, it is often difficult to assess the quality of functioning enterprise: compliance between quality of products (goods or services) to set requirements, correct and transparent business management, activities to improve the functioning of business processes, correct record keeping, competence and satisfaction of employees, and, finally and most importantly, customer satisfaction. DHS also has difficulties arising from specific feature of activity – presence of feedback: heat carrier (water) heated to certain temperature at CHP heating units is transported and distributed to consumers of thermal energy, while returning to source of heat with residual temperature. As main purpose of DHS functioning is to ensure the high-quality and reliable heat supply of consumers (in the most cost-efficient way compliant with environmental standards), there is a need for system ensuring the achievement of this goal and assessing the quality of functioning business. In the world community, Quality Management System (QMS) is considered to be such system.

QMS is designed to ensure the sustainable success of organization and provides the manager with opportunity to analyze the performance of enterprise and production of competitive products; employees – with opportunity to evaluate the results of their actions and be aware of relevance and importance of actions taken; consumers – with opportunity to assess the meeting of requirements related to products and/or services.

QMS ensures the quality management of services – via management of processes [1] forming the quality. This is possible at implementation of basic management functions [5]: interaction with external environment, forming a policy and planning of quality, training and motivation of staff, arrangement of quality-ensuring activities, quality control, information on quality, development and implementation of actions on improving the quality of services. All these functions are interrelated and form a quality management process within the enterprise.

While reviewing this system (QMS) as management object, let us provide its block diagram:

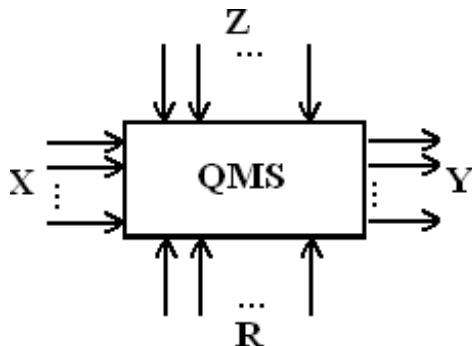


Fig. 1. Block diagram of QMS control

where  $X=(x_1, x_2, \dots, x_n)$  – input requirements to system: requirements to documentation, work of staff, quality of services, etc.;

- $Y=(y_1, y_2, \dots, y_q)$  – output data for system analysis (audit) and monitoring;
- $Z=(z_1, z_2, \dots, z_p)$  – disturbances: critical and emergency situations, human errors, untimely or inadequate (to input requirements) service of providers.
- $R=(r_1, r_2, \dots, r_m)$  – resources needed to meet the system requirements and obtain the necessary results (resources intended for preventive and corrective actions).

Full description of the system consists of mathematical model (control object) used for purposeful conversion of input data to outputs – subject to disturbances and resources.

In scientific research, function is the most common model of transforming the input to output. Classic formalized (explicit) representation of function in mathematics

$$Y=f(X, Z, R),$$

If we transfer the mathematical concept of function to process and correlate it with definition of the process under ISO 9000, the above expression can be interpreted as follows: given the process inputs  $X$ , convert them to output  $Y$  according to conversion rule  $f$ .

As seen from Figure 1, overall structure of the process can be formally represented by two components:

- objects – inputs ( $X, Z, R$ ), outputs ( $Y$ ) answering the question "what"
- functions – conversion rules  $f(X, Z, R)$  answering the question "how".

Function is a specific model (representation) of process describing the rules of transforming the inputs to process output. In other words, the function describes how and what should be done as part of the process – for output (product) to be compliant with certainly set requirements.

In contrast to mathematical function, function related to process shall determine the following:

- what types of input objects must be received at the input of process and without which categories and (or) specific objects the function cannot be implemented?;
- under what rules and into what relations are involved the various categories of input objects during implementation of the process?

It is obvious that, from two identified components, function is the most complete representation of the process, which indirectly comprises the objects too. Therefore, for the purpose of evaluation, analysis, and improvement, each process (activity, work, operation, action, etc.) may be represented in the form of its model – function. The function acts as uniform building block used to construct the process and its components.

For consistent perception of complex process and ease of its analysis, "functions" at each level of hierarchy shall belong to the same class, i.e., have the same set of properties [6].

Projection of formal description to real materialized process enables the control of output compliance. For example, processes of high-quality heat supply can be subject to application of measurable quality parameters (projections at the output). Deviation of resulting features from set parameters demands the correction of process description, reconfiguring of processing parameters, and bringing the characteristics to normal.

The system (QMS) shall be adequate to object and have an opportunity for integration with other management systems.

According to international standard ISO 9001, QMS introduction assumes the following milestones:

- development of quality objectives;
- description of main and auxiliary processes;
- development of process indicators;
- development of QMS documentation;
- familiarizing the staff with documentation;
- keeping the QMS documents up to date;
- collection of measurement results;
- planning and conducting of internal audits;
- data analysis;
- development of corrective and preventive actions, addressing of inconsistencies;
- improvement.

In QMS, one of management principles is use of process approach to description and management. Use of process system along with identification/interaction of the processes (within the enterprise), as well as their management aimed at obtaining the desired result, can be viewed as "process approach" [2]. Dynamic development of market and environment keeps bringing the managers to idea that management of enterprise is a set of business processes defining the essence of activities within organization.

Business process is understood as sustainable and targeted set of interrelated activities using certain technology to transform the resources (materials, funds, equipment, personnel, information) into result (product, service) being of value to consumer or enterprise. The following is necessary to implement the process approach:

1. Identify the main and auxiliary processes affecting the management quality and efficiency, as well as the processes related to consumer;
  2. Identify the persons responsible for planning, analysis, and development of recommendations on process improvement (owners); provide them with necessary authorities;
  3. Determine the process goals – based on objectives of organization;
  4. Set the process boundaries, inputs, and outputs;
  5. Develop the process documents (procedures, rules, maps, diagrams, etc.);
  6. Develop a management, monitoring, and process measuring system;
  7. Provide the processes with necessary resources and run the processes;
  8. Control the processes via monitoring and measurement;
- Plan and implement the process improvements – based on Deming cycle (PDCA cycle).

While breaking the activities of HS enterprise to processes, we get the following: planning, design, production, purchasing management, analysis, and control.

Process approach, along with general ideology, includes description of activities, as network of interrelated processes, and permanent monitoring, management, and improvement of processes. For high-quality management of business processes, they shall be provided with compliant indicators of functioning and efficiency. These figures shall meet the set requirements, deviation from which is considered as incompliance. QMS system shall collect information on values of process indicators and revealed non-conformities.

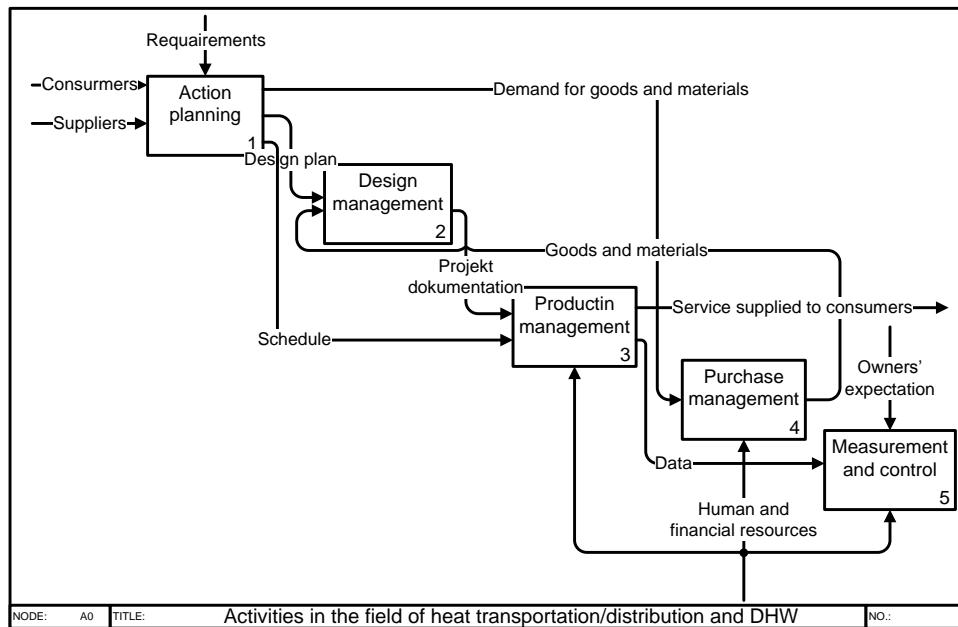


Fig. 2. Business processes of HS enterprise

In case of incompliance, mandatory procedures shall include identification of consequences and causes, significance of which can be estimated by grading system. Quite often, assessment uses a method of analyzing the incompliance, its consequences, and causes (FMEA – Failure Mode and Effects Analysis) – with use of cause-and-effect Ishikawa diagram (introduced in MS ISO 9004-4:94), which applies the risk priority number (RPN). Emergence of incompliance can be dependent on many factors. At that, some of them may affect the others, i.e., be bound with cause-and-effect relations. Definition of entire cause chain can successfully solve a management problem – including the quality management. So, FMEA method on analysis of activity recommends corrective and preventive actions to reduce the severity of consequences or likelihood of failure for the enterprise.

### 3. Conclusion

Thus, QMS establishment in heat supply will ensure:

- permanent improvement of activities via maximum satisfaction of customers, employees, owners, and society;
- improvement of heat supply management;
- energy savings and energy efficiency throughout the life cycle of services;
- growth of financial indicators – at reduction of costs;
- efficient control of business management at heat-supply enterprise;
- improved reliability of HS functioning.

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## DETERMINATION OF THE STRUCTURE OF TASKS FOR PHOSPHORIC ORE SMELTING FURNACE CONTROL

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**Abstract.** The article is devoted to definition of the structure of problems of a control system by the ore-smelting furnace for melting of phosphoric raw materials. The solution of this task is offered to be carried out on the basis of decomposition methods with use of mathematical models of the process.

**Keywords:** ore-smelting furnaces, electric smelting, control of the ore-smelting furnace, mathematical model

### OKREŚLENIE STRUKTURY ZADAŃ STEROWANIA PIECEM DO WYTAPIANIA RUD FOSFORU

**Streszczenie.** Artykuł poświęcony jest omówieniu struktury zadań sterowania piecem do wytapiania rud fosforu. Zaproponowano rozwiązywanie tego zadania w oparciu o metody dekompozycji z wykorzystaniem modelowania matematycznego procesu.

**Slowa kluczowe:** piece do wytopu rud, wytapianie elektryczne, sterowanie piecem do wytopu rudy, model matematyczny

### Introduction

Ore-smelting furnaces for melting raw materials are widely used in the phosphate industry. Increasingly stringent requirements (including environmental and economic) are currently applied to the effectiveness of functioning and quality of products of these furnaces and that cannot be done without the use of modern management techniques and the creation of systems of automation with the use of modern technological means, especially computers and controllers (SCADA-systems).

Phosphoric ore-smelting furnace (POSF) of an enclosed type is characterized by the limited availability of control of process variables, insufficient level of study, aggressive environment and potential dangers. As an object of control, a phosphoric ore-smelting furnace is a complex multi-dimensional dynamic industrial complex, which has a considerable inertia, close interrelationship of input and output variables, significant level of disturbances and limited traceability of a large number of variables [1].

The composition of the vector of process input variables includes such variables as the consumption of phosphorite, electrode paste, phosphorite compositions, quartzite, coke, ashes of reductant; type of raw material used and maximum generating capacity of furnace facility.

The vector of output variables of technological flows of the process includes the following:

1. the variables that can be calculated using a mathematical model of the process: the yield and composition of the slag, dust, ferrophosphorus and a yield of phosphorus; mass and volume yield of the furnace gas, its density, mass and mass change of carbonaceous layer; total specific energy consumption, the content of  $P_2O_5$  in slag, power consumption of the furnace facility, electrical efficiency, linear consumption of electrodes;
2. the variables that can be measured: strength of current; position of electrodes; volumetric gas yield; higher harmonics in the electrodes current, the temperature of furnace gas, electric power consumption (according to electric meter), the amount of electricity consumed between electrodes slipping, power consumption during closed slag tap holes according to meter reading.

The vector of control variables include: consumption of coke and quartzite, changing capacity of the furnace by moving the electrodes (for changing current intensity) or switching voltage levels of the furnace transformer (linear voltage at the electrodes), flushing of slag and outflow of ferrophosphorus.

Significant disturbing influences include: random fluctuations of component composition of furnace charge (chemical and granulometric content of furnace charge, ash content and humidity of furnace charge); power surges in the supply network, fistulas,

sintering and collapses of furnace charge. As a result of these factors, the amount of reacted carbon in the reaction space of the furnace is changed, which in turn, leads to a vibration of resistance of sub-electrode space defined by the mass of carbon layer [2].

### 1. Formulation of the problem

Existing ore-smelting furnace (for melting phosphoric raw materials) automation systems usually solve the problems of monitoring and control of individual technological variables and process control is based on an intuitive, mainly qualitative perception of the characteristics of furnace condition by service personnel [3]. Predictive mathematical models of the process are not used, and therefore, there is no proper efficiency of operational control. Subjective nature of the process assessment leads to a very approximate, often incorrect determination of control actions, resulting in deviations from nominal progress of the process [5]. Adjustment of quartzite and coke dosages is based on the results of chemical analysis of the composition of slag (after draining it from the furnace). The lack of efficiency in determining the composition of the slag leads to a large time lag between changes in the composition of the melt and the need to adjust the composition of furnace charge. The disadvantages of POSF electrical control system mode of operation include the lack methods and algorithms for informed decision making on the optimal ratio of current and voltage for a given capacity of the furnace. It should be noted the absence of any relationship between the problems being solved, because the variables of control and regulation are selected at the level of local design decisions.

In this regard, there is a need to formalize the selection of control problems structure through the application of mathematical models and modern technical means of automation.

### 2. Decomposition of the problem

Considerable inertia of the process, high level of disturbing influences, failure to ensure operational control of several important process variables determines the complexity of the control problem for ore-smelting furnace. In this regard, the decision of this problem is proposed to carry out based on mathematical models of the process with determining interrelated composition solved on the basis of decomposition methods [4].

The structure of automation system for ore-smelting furnace (for smelting phosphoric raw materials) tasks was determined on the basis of systematic analysis of technological complex as the control object, the nature of occurring physical and chemical processes, dynamic properties of the control channels, their

relationship with each other and with regard to the nature of mathematical description of the object. The use of a systematic approach to the synthesis of complex automation system structure for ore-smelting classified as "complex" (in system analysis terms) allows to the greatest extent take into account peculiarities of their interrelated management. At the same time possibilities of technical means of control and management were taken into account [6].

Structuring a control system (allocation of tasks and subsystems) was performed on the basis of determining (forming) of control and recording and management objectives for each manufacturing operation, i.e. by building "objectives tree", from general (increasing the efficiency of the smelting process as a whole at the top control level), to particular (control and recording and providing stabilization of selected modes) objectives at lower levels.

Achieving selected objectives of top-level is provided through achieving the objectives of lower levels (provided there is a consistency of these objectives). Definition of the system functioning objectives (and tasks to be solved respectively) at lower levels of control is carried out in accordance with the principles of technological and structural and temporal decomposition for the following backbone properties:

- history of individual operations for loading materials to the furnace, melting them and receiving products;
- slots for solving monitoring and control tasks (current and operational tasks), solving tasks at regular intervals taking into account dynamic characteristics of the control channels.

The depth of decomposition was assigned as a condition for achieving such a degree of detailing the objectives, which allows connecting the implementation of "the lower branches of objectives tree" with the specific tasks of monitoring, recording and control that should be addressed in the system. As a result, on the basis of this "objectives tree" control requirements were determined by the structure of the control system of ore-smelting furnace as a well-ordered set of problems being solved in the system.

Based on this approach, it was determined that the automation system of ore-smelting furnace to be formed as a hierarchical multilevel system. At the top level, the control tasks of technological complex as a whole are solved, which consist in the need of completing shift-day targets for the production of primary products and other melting products. At the lower level, tasks of control and stabilization of designed process conditions are solved.

In accordance with these principles, two groups of interrelated tasks in the general problem of ore-smelting furnace control were identified (Figure 1):

- Control of melting process conditions;
- Control of energy mode.

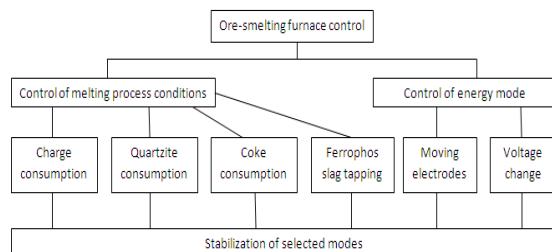


Fig. 1. Structure of phosphoric ore-smelting furnace control tasks

The task of control of melting technological process consists in determining the flow ratio of material flow (consumption of charge, coke, quartzite in the furnace) taking into account their current composition and condition of the furnace (nominal electric capacity of the furnace, the amount and composition of output products - waste gases, slag and ferrophos). The main interval for solving the task - the change, with the clock adjustment,

if necessary. Solving the task is carried out on the basis of the static predictive mathematical model based on the equations of the material balance of the process.

Substantial statement of tasks of energy mode control for electric furnace is formulated as follows: to determine the amount of penetration of the electrodes (conductivity below the electrodes) for a given (current) rates of consumption and chemical composition of the charge, minimizing specific energy consumption under restrictions on smelting rate, the loss of phosphorus with the dump slag, the overall capacity of the furnace, the phase voltage.

Energy mode control is carried out by changing voltage level at the transformer and moving the electrodes to maintain a given current load.

The lower level of control structure is represented by tasks of stabilization of selected modes, with the tasks of monitoring process variables.

### 3. Conclusion

Based on the decomposition methods, the structure of tasks for the system of ore-smelting furnace (for smelting of phosphoric raw materials) control was determined. Were formulated meaningful tasks settings for control of technological and energy modes of the smelting process, the solution of which is expected to use mathematical model of the process control channels.

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## CONSTRUCTION METHOD OF OPTIMAL CONTROL SYSTEM OF A GROUP OF UNMANNED AERIAL VEHICLES

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**Abstract.** In the following work the authors implement mathematical representation of a control system of complex dynamic system. An example of such system is a group of unmanned aerial vehicles. The sufficiency of controlled object mathematical representation is implemented, using the system approach, which in turn describes system elements, taking into account all the relations between them.

**Keywords:** controlled object, control systems, Laplace transformation (LT), unmanned aerial vehicle (the UAV)

### METODY TWORZENIA OPTYMALNEGO SYSTEMU KONTROLI GRUPĄ BEZZAŁOGOWYCH STATKÓW POWIETRZNYCH

**Streszczenie.** W prezentowanej pracy autorzy wdrażają matematyczny opis systemu kontroli złożonego systemu dynamicznego. Przykładem takiego systemu jest grupa bezzałogowych samolotów. Zaimplementowano odpowiedni opis matematyczny kontrolowanego obiektu stosując podejście systemowe, które opisuje wszystkie elementy systemu uwzględniając wszystkie relacje między nimi.

**Słowa kluczowe:** obiekt kontrolowany, system sterowania, transformata Laplace'a, bezzałogowe statki powietrzne

### Introduction

Characteristic features of team flight of unmanned aerial vehicles (the UAV) with consideration for the possibility of failure of data channel as the controlled object [1-3]: the lack of full mathematical representation of occurring changes; random nature of processes and non-stationariness of parameters allow considering it as a complex system.

It is noted that adequate general approach to solving control tasks related to the complex object functioning is an application of system approach.

### 1. Problem analysis

The main principle of systematic control task solving is decomposing complex systems into conventional "small" elements and synthesis of control with the condition of consideration of all relations between elements.

Implementing systematic approach assumes adequate mathematical representation of controlled object, which allows to describe elements of the system and take into account all the relations between them.

In the theory of automatic control systems two basic types of mathematical representation of objects and control systems are being used. The first type lies in representation of processes in the frequency domain, in the "space of signals", when all the elements features are determined by the transfer functions. This type of representation is focused on solving tasks of stabilization, when the program trajectory is a priori known; the object allows linearization with a small deviation from it and the necessary parameters of the transition process have to be ensured. Despite its widespread use, the disadvantage of such representation lies in the fact that it does not allow taking into account an integrated use of all available resources in a closed autonomous dynamic system and solving current tasks of automatic control with object functions.

For the synthesis of optimal control "in large" when it is necessary to simultaneously determine the best program trajectory and implement stabilization on it, the second method of mathematical representation, namely the state of space method is used. Under the terms of this method, the mathematical system model, which reflects the characteristics and existing restrictions, should be represented in the state of space - a metric domain, each element of which fully determines the state of the considered system.

Such representation allows using both classic (various methods of variational calculus), and modern methods of optimization (principle of maximum, generalized work method, method of analytical design of optimal regulators). Therefore, in order to conduct a research, the mathematical model, where the state vector includes the phase coordinate of the system in state of space, has been used. The possibility of applying the principle of separation for closed dynamical systems, presented in the space of phase states, is of importance.

### 2. Problem solving

With respect to controlled coordinate, generalized controlled object, for short hereinafter referred to as object, can be described by equation of the form:

$$y^{(n)} + \sum_{i=0}^{n-1} a_i(t) \cdot y^{(i)} = \sum_{j=0}^m d_j(t) \cdot x^{(i)}, \quad (1)$$

where  $x$  is a controlling action;  $y$  is an output coordinate;  $a_i(t)$ ,  $d_j(t)$  are coordinates variable in time, or in operator form

$$A(p,t)Y(p) = D(p,t)X(p), \quad (2)$$

where  $A(p,t), D(p,t)$  are linear differential operators.

Note that the equation of the form (1) or (2) can describe the motion of many objects, including aerial vehicles. A linear mathematical model of the object motion relative to the estimated trajectory is correct only under certain restrictions imposed on object signals and coordinates, range and rate of change of its coefficients. The said restrictions can be described in the form of inequations

$$B_k[p, g, y, x, a_i(t), d_j(t), t] \leq 0,$$

where  $B_k$  is some operators,  $g$  is incoming signal,  $p$  is a parameter of Laplace transformation,  $t$  is current time.

Taking into account the laws of control, the equation of primary system takes on the appearance on

$$y^{(n)} + \sum_{i=0}^{n-1} [a_i(t) + C_i(t)] y^{(i)} = \sum_{j=0}^m [d_j(t) + Cx_j(t)] x^{(j)}. \quad (3)$$

Put the case of rebuilt coefficients  $C_i(t)$  and  $Cx_j(t)$  in the form of sum of two components

$$\begin{cases} C_i(t) = \bar{C}_i(t) + \Delta C_i(t); \\ Cx_j(t) = \bar{C}x_j(t) + \Delta Cx_j(t), \end{cases} \quad (4)$$

where  $\bar{C}_i(t), \bar{C}x_j(t)$  are invariables,  $\Delta C_i(t), \Delta Cx_j(t)$  are rebuilt components. By introducing notation

$$\begin{cases} a_i = a_i(t) + \bar{C}_i; \\ d_j = d_j(t) + \bar{C}x_j, \end{cases}$$

to the formulas (3) and (4), it is possible to set down

$$y^{(n)} + \sum_{i=0}^{n-1} [a_i(t) + \Delta C_i(t)] y^{(i)} = \sum_{j=0}^m [d_j(t) + \Delta Cx_j(t)] x^{(j)}. \quad (5)$$

Changes of equation coefficients  $a_i$  and  $d_j$ , caused by changes in the parameters of the object, will be balanced out by the relative changes in coefficients  $\Delta C_i(t), \Delta Cx_j(t)$  to values, defined by the model. The equation of a master model can be represented as follows

$$y_m^{(n)} + \sum_{i=0}^{n-1} b_i y_m^{(i)} = \sum_{j=0}^m d_{jm} x^{(j)}, \quad (6)$$

where  $b_i, d_{jm}$  are the model equation coefficients, independent of time.

If you select the desired values of coefficients equal to model coefficients, and their additional components, the formula (3) shall be reconstructed into the form

$$\begin{aligned} y^{(n)} + \sum_{i=0}^{n-1} [b_i(t) + \Delta a_i(t) + \Delta C_i(t)] y^{(i)} &= \\ &= \sum_{j=0}^m [d_{jm}(t) + d_j(t) + \Delta Cx_j(t)] x^{(j)} \end{aligned} \quad (7)$$

Deviation of main system output, and the model  $\varepsilon = y - y_m$  shall be calculated, using the equations (6) and (7):

$$\begin{aligned} \varepsilon^{(n)} + \sum_{i=0}^{n-1} b_i \varepsilon^{(i)} &= \sum_{j=0}^m [\Delta d_j(t) + \Delta Cx_j(t)] x^{(j)} - \\ &- \sum_{i=0}^{n-1} [\Delta a_i(t) + \Delta C_i(t)] y^{(i)} \end{aligned} \quad (8)$$

By grouping members of equation (8), we deduce

$$\begin{aligned} \varepsilon^{(n)} + \sum_{i=0}^{n-1} b_i \varepsilon^{(i)} &= \left[ \sum_{j=0}^m \Delta d_j(t) x^{(j)} - \sum_{i=0}^{n-1} \Delta a_i(t) y^{(i)} \right] + \\ &+ \left[ \sum_{j=0}^m \Delta Cx_j(t) x^{(j)} - \sum_{i=0}^{n-1} \Delta C_i(t) y^{(i)} \right]; \end{aligned} \quad (9)$$

$$\varepsilon^{(n)} + \sum_{i=0}^{n-1} b_i \varepsilon^{(i)} = F + U, \quad (10)$$

where  $F = \left[ \sum_{j=0}^m \Delta d_j(t) x^{(j)} - \sum_{i=0}^{n-1} \Delta a_i(t) y^{(i)} \right]$  is an equivalent disturbance, affecting the system and which causes an error;

$U = \left[ \sum_{j=0}^m \Delta Cx_j(t) x^{(j)} - \sum_{i=0}^{n-1} \Delta C_i(t) y^{(i)} \right]$  – is an equivalent impact of control device.

In order to simplify the results, by introducing notation  $\varepsilon^{(i)} = x_{i+1} (i = 0, 1, \dots, n)$ , an error equation (10) can be represented in matrix form

$$\begin{aligned} \dot{X} &= AX + U, \\ \text{where } X &= \begin{vmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{vmatrix}, \quad U = \begin{vmatrix} 0 \\ 0 \\ \vdots \\ U_0 \end{vmatrix} \\ A &= \begin{vmatrix} 0 & 1 & 0 & \dots & \dots & \dots & 0 \\ 0 & 0 & 1 & \dots & \dots & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \ddots & \ddots & \vdots \\ -b_0 & -b_1 & -b_2 & \dots & \dots & \dots & -b_{n-1} \end{vmatrix} \end{aligned}$$

A task of adaptive functional and stable complex synthesis can be reduced in this case to the choice of such control, whereby the equalization of equivalent disturbance  $F$  is taking place.

The principle of distribution, which is fundamental for the synthesis of optimal linear systems, can also be applied by the synthesis of optimal functional and stable control of the UAV's team flight.

Among the three control channels of the UAV's team flights: the distance, interval and exceedance, the distance control channel, due to the high response rate, as well as significant and asymmetrical constraints on the control signals during acceleration and braking action of aerial vehicles, is distinguished by technical implementation complexity. In this regard, the argumentation for applying the principle of adaptation in the systems of the UAV group piloting and all subsequent researches will be conducted through the example of distance control channel between the UAV.

In general case, distance control between the UAV must be coordinated, i.e. distance change should be made through simultaneous effect on diving-rudder and engine thrust. In order to implement such control, the signals, proportional to pitch attitude angle, flight altitudes and flight-speed should be given to channels of rudder and thrust.

In this case the motion equation can be introduced as:

$$\begin{cases} \delta_P = q_{11}(P)d + q_{12}(P)V + q_{13}(P)h - y_1; \\ \delta_\theta = q_{21}(P)d + q_{22}(P)V + q_{23}(P)h - y_2, \end{cases}$$

where  $q_{ik}(P) (i = 1, 2; k = 1, 2, 3)$  are the transfer functions of engine thrust and diving-rudder control systems;  $d, V, h$  are current values of distance, pitch attitude angle and altitude respectively;  $y_i$  is the signals by trajectory program.

In case when the flight altitude and angular motions of aerial vehicles are stabilized by the quick-responding autopilots, the angular motions have no effect on the motions of aerial vehicle mass center, and to control the distance you can use automatic machine, which affects the engine thrust; the equation of this automatic machine will be [6]:

$$\delta_P = q_{11}(P)d - y_1$$

Distance stabilization loop is relatively low frequency. As a result, there is no need to consider small parameters of this

loop. In particular, for the engine the simplest transfer function of inertia links can be used:

$$W_{DW}(P) = \frac{K_{DW}}{T_{DW}P+1},$$

where  $K_{DW}$ ,  $T_{DW}$  are the augmentation ratio and time constant of aircraft engine respectively.

Thus, the analysis of the dynamic properties and characteristics of the UAV's team flight while providing functional and stable control with consideration for the possibility of data channel, shows that it is possible to divide the UAV's team flight control into three independent channels: the distance, exceedance and interval control between the UAV.

Furthermore, the distance control channel has been analyzed. This allows limiting the dimension of the following model and the complexity of obtained algorithms.

The failures of sub-systems of closed-loop regulating system in theory can be represented by different models [4-8]. Additive models, where the failure is represented by a vector of accidental variations in phase coordinates of a system  $\gamma(t)$  of the form

$$\begin{cases} \dot{X}(t) = A(X,t) \cdot X(t) + B(X,t) \cdot U(t) + \xi(t) + \gamma(t); \\ Y(t) = H(t) \cdot X(t) + \eta(t) + \gamma(t), \end{cases} \quad (11)$$

are inconvenient to describe the data channel failure, since they do not allow taking into account the characteristic, specific features of the considered failures (in this case a model of the form (11) can not take into account a variation in quantity of a data update time  $T_D$ ).

Models of the form

$$\begin{cases} \dot{X}(t) = A^s(X,t) \cdot X(t) + B^w(X,t) \cdot U(t) + \xi(t); \\ Y(t) = H^f(t) \cdot X(t) + \eta(t); \end{cases}$$

which take into account the failure by structure change of the dynamic matrix of a system  $A^s(X,t)$ , control matrix  $B^w(X,t)$  and measurements matrix  $H^f(t)$ , are more suitable to the physical nature of the processes in the data channel.

Since the data channel failures mean an increase, over the permissible duration, in data update time between base components and the actual UAV  $T_D$ ,  $H_i(t)$  can be described as:

$$H_i(t) = \begin{cases} H_0 & \text{at } T_D \leq T_D^{\lim}; \\ H_1 & \text{at } T_D^{nop} > T_D > T_D^{\lim}. \end{cases}$$

In addition, this model can not take into account the causes of failures (because of enemy counterglow or dysfunction of communication technology) and a priori unknown statistical characteristics of failures.

The principle of distribution, applied for decomposing the controlled object into sealed channels, can be used in order to divide control tasks into two sub-tasks: the formation of program trajectory and stabilization on it. Moreover, by distance stabilization the most important is minimizing the errors of program trajectory exercise. Therefore, the weight coefficients of the first component of the performance function should be significantly greater than the weight coefficients of the second component. Thus, the minimization of performance function of the form

$$I(X(t), U(t) / H_i(t)) = M \left( \int_{t_0}^{t_k} X^T(t) \cdot \beta \cdot X(t) dt \right);$$

i.e. without the component, corresponding to the expenses on control, has been carried out in the following work.

### 3. Conclusions

Methodical basis for construction of the optimal functional and stable control of the group of the UAV is to use the system approach and the principle of decomposition as the theory of complex technical systems construction.

The structure of optimal functional and stable control of the group of the UAV with consideration for the possibility of data channel failure must include, in addition to the controlled object (the group of the UAV) and a trilateration measuring system, a relative model based on the extrapolation of the relative position in the group and optimal regulator, which implements the algorithm of optimal control.

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# ANALIZA MODELU UŁAMKOWEGO RZĘDU PROCESÓW SZYBKICH REAKTORA JĄDROWEGO

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**Streszczenie.** W artykule przedstawiono wyniki badań dotyczące rozwiązań numerycznych punktowego modelu ułamkowego rzędu kinetyki neutronów oraz wymiany ciepła w reaktorze jądrowym. Zbudowano model ułamkowego rzędu z sześcioma grupami neutronów opóźnionych wraz równaniami wymiany ciepła. Model matematyczny został zaimplementowany w środowisku Matlab i zbadany symulacyjnie dla skoków reaktywności. Przeprowadzono analizę wpływu wybranych parametrów modelu na uzyskiwane rozwiązania.

**Słowa kluczowe:** rachunek ułamkowy, reaktor jądrowy, równania różniczkowe

## FRACTIONAL MODEL OF FAST PROCESSES IN NUCLEAR REACTOR ANALYSIS

**Abstract.** The paper presents the results concerning numerical solutions of the fractional point kinetics and heat exchange model for nuclear reactor. The fractional neutron point kinetics model with six groups of delayed neutron precursors was developed and numerical solutions were proposed. Mathematical model has been implemented in the Matlab environment and tested using typical step input change. The analysis of the impact of chosen parameters was conducted.

**Keywords:** fractional calculus, fission reactors, differential equations

### Wstęp

Zasadnicza różnica pomiędzy elektrowniami cieplnymi konwencjonalnymi i jądrowymi wynika z rodzaju procesów wykorzystywanych do generacji ciepła. W elektrowniach cieplnych są to procesy spalania mediów organicznych w energetycznych kotłach parowych. W elektrowniach jądrowych (EJ) są to procesy łańcuchowej reakcji rozszczepienia jąder izotopów, nazywanych paliwowymi, zachodzące w rdzeniu reaktora jądrowego. Para, wykorzystywana dalej do zamiany energii cieplnej na mechaniczną w turbinach, wytwarzana jest bądź bezpośrednio w reaktorze – elektrownie z reaktorami wrzecionymi, bądź w wytwarzni pary – elektrownie z reaktorami ciśnieniowymi, dla której chłodzivo reaktora jest źródłem ciepła. W EJ z reaktorami ciśnieniowymi obieg chłodziva, które odbiera ciepło generowane w rdzeniu reaktora zamknięta się w tzw. obiegu pierwotnym obejmującym reaktor i wytwarznię pary. Pomiędzy zespołami turbina - generator w elektrowniach cieplnych na paliwo organiczne i na paliwo jądrowe nie ma funkcjonalnych różnic. Zasadniczymi procesami zachodzącymi w rdzeniu reaktora są procesy związane z łańcuchową reakcją rozszczepienia. Ich osią jest proces rozszczepiania jąder izotopów paliwowych. Akt rozszczepienia jądra izotopu paliwowego, wywołany pojedynczym neutronem jest źródłem 2-3 neutronów nowego pokolenia o wysokich energiach. Powszechnie dziś stosowane reaktory jądrowe lekko wodne wykorzystują do rozszczepiania jąder neutronów o niskich energiach – neutronów termicznych. Należy je spowolnić do poziomu energii termicznych w procesie dyfuzji w środowisku rdzenia reaktora. W tym celu jako medium moderujące wykorzystywana jest, w reaktorach lekko wodnych, woda przepływająca w przestrzeni pomiędzy prełami z materiałem rozszczepialnym. Pełni więc ona w EJ tego typu podwójną rolę – chłodziva i moderatora. Natomiast ze względu na czas pojawiania się neutrony dzielą się na natychmiastowe i opóźnione. Pierwsze z nich (ponad 99% neutronów rozszczepieniowych) emitowane są bezpośrednio w akcie rozszczepienia, natomiast neutrony opóźnione (mniej niż 1%) powstają przy rozpadzie promieniotwórczym określonych produktów rozszczepienia – prekursorów neutronów opóźnionych. W skali makroskopowej relację pomiędzy liczebnością kolejnych pokoleń neutronów w rdzeniu reaktora określa efektywny współczynnik mnożenia neutronów  $k_{ef}$ . Jego wartość równa jeden oznacza generowanie w rdzeniu reaktora energii jądrowej z taką samą intensywnością, czyli generowanie stałej mocy. Jego wartość większa od jedności oznacza wzrastanie mocy reaktora, a mniejsza od jedności jej malenie. Dla stanów pracy reaktora ze stałą mocą stosuje się częściej inną wielkość dla charakteryzowania relacji pomiędzy

liczebnością neutronów w kolejnych pokoleniach – reaktywność  $\rho$ . Definiuje się ją jako względne odchylenie efektywnego współczynnika mnożenia neutronów od jedności, czyli:

$$\rho = \frac{k_{ef}-1}{k_{ef}} \quad (1)$$

Matematyczne opisy procesów łańcuchowej reakcji rozszczepienia nazywają się modelami kinetyki neutronów. Aproxymacja punktowa tych procesów operująca wartościami średnimi wielkości nazywana jest modelem punktowym kinetyki neutronów.

Prace badawcze dotyczące modelowania ułamkowego rzędu trwają od wielu lat i doczekały się licznych publikacji. Obszarem zainteresowania są często złożone układy nieliniiowe. Wymień można tutaj model jonowych metalowych kompozytów, układów elektrycznych [4], filtrów elektrycznych [8], układów regulacji [10], w tym regulatorów ułamkowego rzędu  $PID^\alpha$  [5]. Przykład estymacji parametrów dla modelu ułamkowego został przedstawiony w [9]. W artykule [8] zaproponowano punktowy model kinetyki neutronów ułamkowego rzędu z jedną grupą prekursorów neutronów opóźnionych.

Artykuł rozważa model punktowy kinetyki z sześcioma grupami prekursorów neutronów opóźnionych wykorzystujący rachunek różniczkowy niecałkowitego rzędu oraz model punktowy wymiany ciepła wykorzystujący rachunek różniczkowy całkowitego rzędu. Podano przy tym wartości poszczególnych stałych parametrów oraz przyjętych warunków początkowych. Przeprowadzono analizę wpływu rzędu pochodnej ułamkowej na przebiegi znormalizowanej gęstości neutronów, temperatury rdzenia oraz reaktywności dla wybranych wymuszeń. Przyjęto, że przed rozpoczęciem badań reaktor znajdował się w stanie krytycznym. Na zakończenie podano wyniki badań oraz wnioski.

### 1. Pochodna niecałkowitego rzędu

Istnieje kilka metod określania pochodnej ułamkowego rzędu. Do głównych należą definicje: Caputo, Riemanna-Liouville'a oraz Grünwalda-Letnikowa [11]. Pochodna niecałkowitego rzędu może być przedstawiona jako [10]:

$$D_t^\alpha = \begin{cases} \frac{d^\alpha}{dt^\alpha} & \alpha > 0 \\ 1 & \alpha = 0 \\ \int_0^t (dt)^\alpha & \alpha < 0 \end{cases} \quad (2)$$

gdzie  $\alpha$  – rzad pochodnej. Należy zauważyć, że dla ujemnej wartości  $\alpha$  następuje całkowanie. W przypadku, gdy  $\alpha$  jest całkowitego rzędu powstaje pochodna lub całka ujęta w klasycznym (całkowitym) ujęciu.

## 2. Punktowa kinetyka reaktora jądrowego

Ułamkowy punktowy model kinetyki reaktora jądrowego z sześcioma grupami prekursorów neutronów opóźnionych, można zapisać następująco [8]:

$$\begin{aligned} \tau^k \frac{d^{k+1}}{dt^{k+1}} n(t) + \frac{d}{dt} n(t) + \tau^k \left( \frac{1}{l} + \frac{1-\beta}{\Lambda} \right) \frac{d^k}{dt^k} n(t) + \\ + \frac{\beta - \rho(t)}{\Lambda} n(t) = \sum_{j=1}^6 \tau^k \frac{d^k}{dt^k} C_j(t) + \sum_{j=1}^6 \lambda_j C_j(t) \end{aligned} \quad (3)$$

$$\frac{d}{dt} C_j(t) = \frac{\beta_j}{\Lambda} n(t) - \lambda_j C_j(t) \text{ dla } j=1, \dots, 6 \quad (4)$$

z warunkami początkowymi:

$$n_0 = n(0); C_{j0} = C_j(0) = \frac{\beta_j}{\Lambda \lambda_j} n_0 \text{ dla } j=1, \dots, 6$$

gdzie  $n(t)$  – gęstość neutronów,  $C_j(t)$  – koncentracja jąder prekursorów neutronów opóźnionych  $j$ -tej grupy,  $\beta_j$  – udział neutronów opóźnionych  $j$ -tej grupy w populacji neutronów,  $\lambda_j$  – stała rozpadu prekursorów neutronów opóźnionych  $j$ -tej grupy,  $l$  – czas życia neutronów natychmiastowych,  $\Lambda$  – efektywny czas życia neutronów,  $\rho(t)$  – reaktywność,  $\tau^k$  – czas relaksacji. Czas relaksacji  $\tau^k$  jest parametrem określającym szybkość powrotu układu do stanu równowagi. Wielkość ta ma zatem charakter stałej czasowej. Wraz ze wzrostem jej wartości układ (w tym przypadku: gęstość neutronów w rdzeniu reaktora jądrowego) będzie powracał do stanu równowagi coraz wolniej.

W tablicy 1 przedstawiono przyjęte udziały neutronów opóźnionych w populacji neutronów i stałe rozpadu ich prekursorów.

Tablica 1. Udziały neutronów opóźnionych i stałe rozpadu ich prekursorów dla U-235 [7]

i	$\beta_i$	$\lambda_i$
1	0,000231	0,0124
2	0,001533	0,0305
3	0,001327	0,1110
4	0,002765	0,3010
5	0,000805	1,1300
6	0,000294	3,0000

Ponadto, w równaniach (3) – (4) przyjęto wartości:  $\beta = \sum_{j=1}^6 \beta_j = 0,007$ ,  $\Lambda = l = 0,000003 \text{ s}$ ,  $\tau^k = 0,0001 \text{ s}^k$ . Wpływ wartości  $k$  na uzyskiwane rozwiązania będzie przedmiotem prezentowanych dalej badań. Prace prowadzono wykorzystując wartości względne zmiennych  $n$  oraz  $C$ , wynikające z założenia  $n_0 = 1$ . Stan krytyczny równowagi, różny od stanu wyłączenia reaktora, przyjmowano każdorazowo za stan początkowy, dlatego też warunki początkowe dla tego stanu wynoszą:  $n_0 = 1$ ,  $C_{10} = 620,97$ ,  $C_{20} = 1675,4$ ,  $C_{30} = 398,5$ ,  $C_{40} = 306,2$ ,  $C_{50} = 23,746$ ,  $C_{60} = 3,2667$ .

## 3. Punktowy model wymiany ciepła

Punktowy model wymiany ciepła w reaktorze jądrowym można zapisać jako układ różniczkowy [7]:

$$M_{ep} c_{ep} \frac{dT_{ep}(t)}{dt} = Q_R(t) - \frac{1}{R} (T_{ep}(t) - T_c(t)) \quad (5)$$

$$M_c c_c \frac{dT_c(t)}{dt} = \frac{1}{R} (T_{ep}(t) - T_c(t)) - 2w(t) c_p (T_c(t) - T_{we}(t)) \quad (6)$$

gdzie  $T_{ep}(t)$  – uśredniona po objętości rdzenia temperatura elementu paliwowego,  $T_c(t)$  – uśredniona po objętości rdzenia temperatura chłodziwa,  $T_{we}(t)$  – temperatura chłodziwa na wlocie do rdzenia,  $M_{ep}$  – całkowita masa elementów paliwowych w objętości rdzenia,  $M_c$  – całkowita masa chłodziwa i elementów konstrukcyjnych w objętości rdzenia,  $c_{ep}$  – średnie ważone ciepło właściwe elementów paliwowych w rdzeniu,  $c_c$  – średnie ważone ciepło właściwe chłodziwa (przy stałym ciśnieniu) i materiałów konstrukcyjnych rdzenia,  $c_p$  – ciepło właściwe chłodziwa (przy

stałym ciśnieniu),  $R$  – oporność cieplna rdzenia,  $w$  – masowy wydatek chłodziwa (przy stałym ciśnieniu).

Powyższy model został znormalizowany tak, by  $T_{ep}(0) = 1$  oraz  $T_c(0) = 1$ . Po normalizacji otrzymano:

$$\frac{dT_{ep}}{dt} = \frac{Q_R}{T_{ep,B} M_{ep} c_{ep}} - \frac{T_{ep} - \frac{T_{c,B}}{T_{ep,B}} T_c}{R M_{ep} c_{ep}} \quad (7)$$

$$\frac{dT_c}{dt} = \frac{1}{R M_c c_c} \left( \frac{T_{ep,B}}{T_{c,B}} T_{ep} - T_c \right) - \frac{2w c_p}{M_c c_c} (T_c - \frac{T_{we}}{T_{c,B}}) \quad (8)$$

Uwzględnienie modelu wymiany ciepła niesie za sobą konieczność wzięcia pod uwagę efektów reaktywnościowych. Jest to zmiana wartości reaktywności wywołana zmianą stanu termicznego rdzenia. Uwzględniając stan krytyczny reaktora przed rozpoczęciem badań  $\rho_0 = 0$ , efekt reaktywnościowy można zapisać jako [7]:

$$\begin{aligned} \Delta \rho &= \rho(t) - \rho_0 = \rho(t) - 0 = \\ &= \alpha_c [T_c(t) - T_{c,B}] + \alpha_{ep} [T_{ep}(t) - T_{ep,B}] \end{aligned} \quad (9)$$

gdzie  $\alpha_c$  – współczynnik reaktywnościowy od zmian temperatury chłodziwa,  $\alpha_{ep}$  – współczynnik reaktywnościowy od zmian temperatury rdzenia. W równaniach (6) – (8) przyjęto wartości:  $M_{ep} = 60645 \text{ kg}$ ,  $c_{ep} = 313,07 \frac{\text{J}}{\text{kgK}}$ ,  $R = 2,325 * 10^{-7} \frac{\text{J}}{\text{C}\cdot\text{s}}$ ,  $M_c = 10573 \text{ kg}$ ,  $c_c = 3402,9 \frac{\text{J}}{\text{kgK}}$ ,  $c_p = 5460 \frac{\text{J}}{\text{kgK}}$ ,  $Q_R = 1375 \text{ MW}$ ,  $T_{we} = 269^\circ\text{C}$ ,  $T_{ep,B} = 603,16^\circ\text{C}$ ,  $T_{c,B} = 283,47^\circ\text{C}$ ,  $\alpha_c = -1,2 * 10^{-4} \frac{1}{^\circ\text{C}}$ ,  $\alpha_{ep} = -3,4 * 10^{-5} \frac{1}{^\circ\text{C}}$ ,  $w = 8700 \frac{\text{kg}}{\text{s}}$ .

## 4. Wyniki badań testowych

Przeprowadzono testy symulacyjne rozwiązania znormalizowanej gęstości neutronów termicznych, temperatury rdzenia oraz reaktywności. Badania przeprowadzono w środowisku MATLAB z użyciem Toolboxa FOMCON. Wybrano go ze względu na jego stary rozwój zarówno w przypadku sterowania jak i oceny stabilności. Wejściem modelu była reaktywność albo temperatura chłodziwa na wlocie do rdzenia. Założono, że początkowym stanem reaktora jest stan krytyczny. Na wejście podano skok reaktywności o wartościach -0,00005 i 0,00005, albo skok temperatury chłodziwa na wlocie do rdzenia o wartościach -2°C i 2°C. Każde z badań przeprowadzono dla różnych wartości pochodnych  $k$  (0; 0,25; 0,5; 0,75). Przyjęto czas symulacji  $t = 150 \text{ s}$ .

Na rys. 1-3 przedstawiono wpływ ujemnej skokowej zmiany reaktywności.

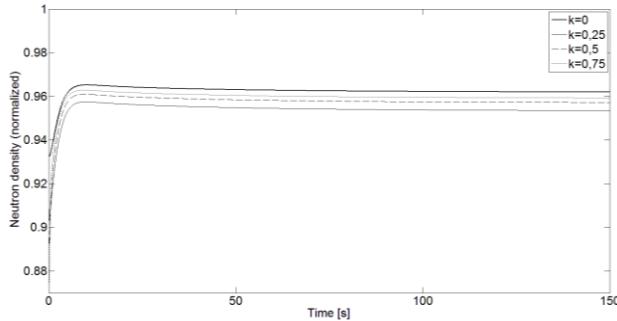
Dla ujemnego skoku reaktywności gęstość neutronów, temperatura rdzenia maleje, zaś dla dodatniego – rośnie. Przebiegi gęstości neutronów dla modeli o różnych wartościach pochodnych  $k$  różnią się od siebie. Z powodu różnej dynamiki gęstości neutronów dla różnych wartości  $k$  różna jest dynamika zmian temperatury rdzenia dla różnych wartości  $k$ . Jest to spowodowane zależnością temperatury rdzenia od gęstości neutronów. Istnienie sprzężeń reaktywnościowych wywołuje zmianę wartości reaktywności. Wraz z dążeniem reaktywności do zera prędkość zmian gęstości neutronów również dąży do zera.

Na rys. 7-9 przedstawiono wpływ ujemnej skokowej zmiany wartości temperatury chłodziwa na wlocie do rdzenia.

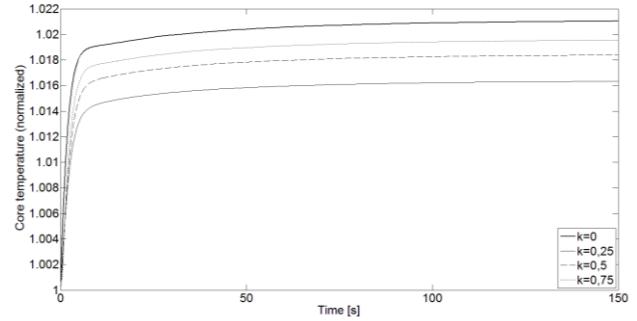
Na rys. 10-12 przedstawiono wpływ dodatniej skokowej zmiany wartości temperatury chłodziwa na wlocie do rdzenia.

Na rys. 4-6 przedstawiono wpływ dodatniej skokowej zmiany reaktywności.

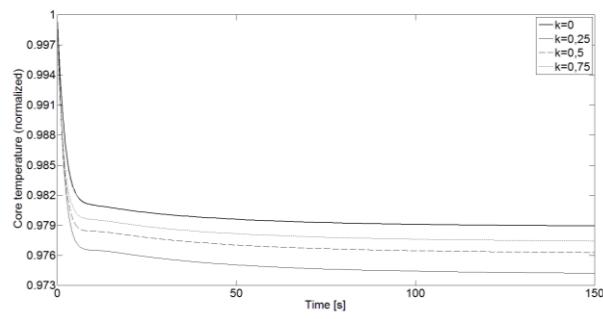
Dla ujemnej skokowej zmiany wartości temperatury chłodziwa na wlocie do rdzenia gęstość neutronów i temperatura rdzenia rosną, zaś reaktywność maleje po uprzednim wzroście. Dla dodatniego skoku – reaktywność rośnie po uprzednim zmniejszaniu wartości, a pozostałe badane wielkości maleją. Przebiegi badanych wielkości ustalają się. Dla różnych wartości  $k$  wartość w stanie ustalonym jest różna. Im wartość  $k$  dla  $k \neq 0$  jest większa, tym przebieg bardziej się zbliża do przebiegu dla  $k = 0$ .



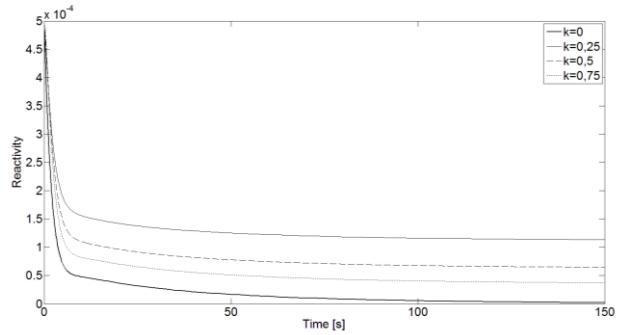
Rys. 1. Przebiegi znormalizowanej gęstości neutronów dla  $\Delta\rho = -0,0005$ ,  $\Delta T_{we}(t) = 0$



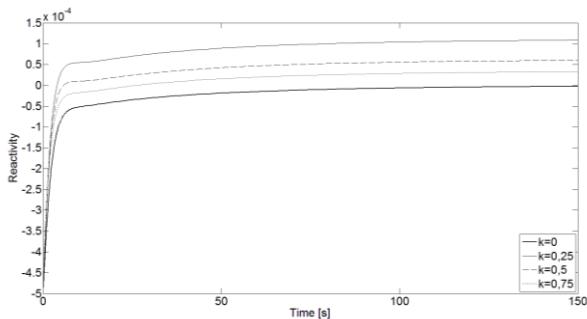
Rys. 5. Przebiegi znormalizowanej temperatury rdzenia dla  $\Delta\rho = 0,0005$ ,  $\Delta T_{we}(t) = 0$



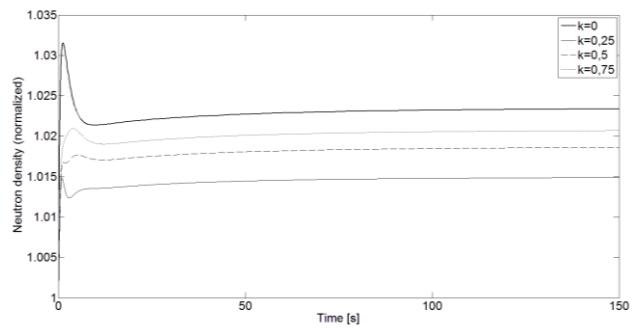
Rys. 2. Przebiegi znormalizowanej temperatury rdzenia dla  $\Delta\rho = -0,0005$ ,  $\Delta T_{we}(t) = 0$



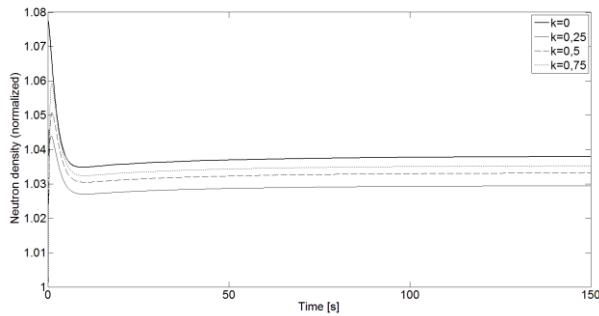
Rys. 6. Przebiegi reaktywności dla  $\Delta\rho = 0,0005$ ,  $\Delta T_{we}(t) = 0$



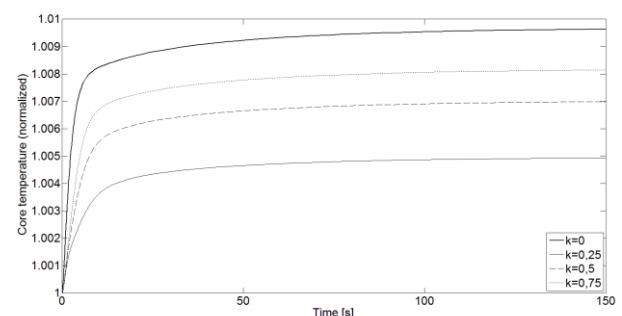
Rys. 3. Przebiegi reaktywności dla  $\Delta\rho = -0,0005$ ,  $\Delta T_{we}(t) = 0$



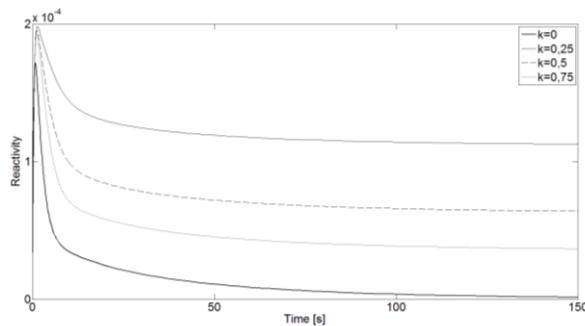
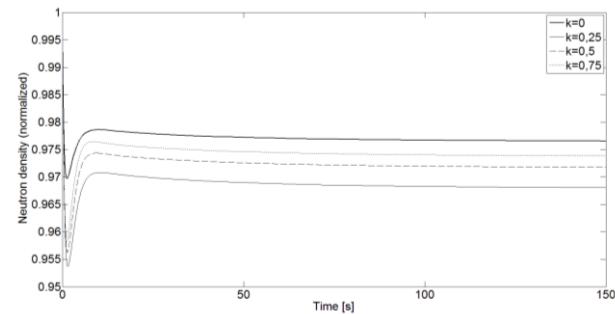
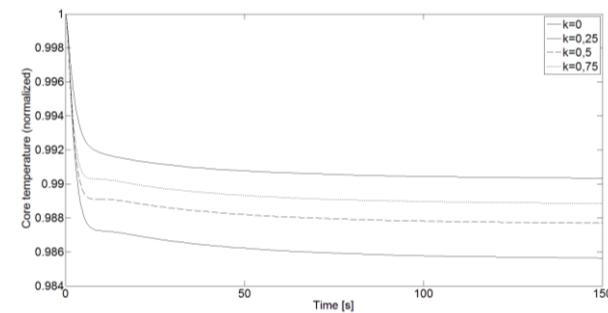
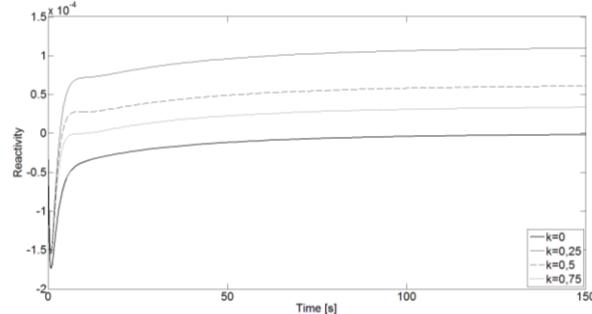
Rys. 7. Przebiegi znormalizowanej gęstości neutronów dla  $\Delta\rho = 0$ ,  $\Delta T_{we}(t) = -2^\circ C$



Rys. 4. Przebiegi znormalizowanej gęstości neutronów dla  $\Delta\rho = 0,0005$ ,  $\Delta T_{we}(t) = 0$



Rys. 8. Przebiegi znormalizowanej temperatury rdzenia dla  $\Delta\rho = 0$ ,  $\Delta T_{we}(t) = -2^\circ C$

Rys. 9. Przebiegi reaktywności dla  $\Delta\rho = 0$ ,  $\Delta T_{we}(t) = -2^\circ\text{C}$ Rys. 10. Przebiegi znormalizowanej gęstości neutronów dla  $\Delta\rho = 0$ ,  $\Delta T_{we}(t) = 2^\circ\text{C}$ Rys. 11. Przebiegi znormalizowanej temperatury rdzenia dla  $\Delta\rho = 0$ ,  $\Delta T_{we}(t) = 2^\circ\text{C}$ Rys. 12. Przebiegi reaktywności dla  $\Delta\rho = 0$ ,  $\Delta T_{we}(t) = 2^\circ\text{C}$ 

## 5. Wnioski

W artykule przedstawiono wyniki badań właściwości rozwiązań punktowego modelu kinetyki neutronów niecałkowitego rzędu wraz z modelem wymiany ciepła. Wykazano budowę struktury obliczeniowej z biblioteki FOMCON. Zbadano wpływ pochodnej niecałkowitego rzędu  $k$  na przebiegi gęstości neutronów, temperatury rdzenia oraz reaktywności dla skokowych zmian reaktywności oraz temperatury chłodziwa na wlocie do rdzenia. Stwierdzono, iż wartość  $k$  wpływa na dynamikę badanych wielkości. Im wartość ta jest większa, tym czas ustalania jest krótszy, a różnica między wartością ustaloną po skoku, a przed skokiem jest mniejsza.

Modele punktowe (o parametrach skupionych) są stosowane powszechnie w analizie i syntezie systemów sterowania realnych reaktorów jądrowych [1, 2, 6, 7, 8, 12]. Dążenie do poprawy jakości sterowania tymi reaktorami wymaga poszukiwania coraz lepszych punktowych aproksymacji w istocie przestrzennych procesów reaktora jądrowego. Modele punktowe wykorzystujące rachunek niecałkowitego rzędu są taką próbą (jak w artykule).

Aktualny wysiłek badaczy skupiony jest na konstrukcji algorytmów aproksymacji modeli 1D [3] i 3D kinetyki neutronów i wymiany ciepła modelami punktowymi niecałkowitego rzędu.

## Podziękowania

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# NUMERICAL ANALYSIS OF ARTIFICIAL HYPERTERMIA TREATMENT

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**Abstract.** This paper presents numerical modelling of artificial hyperthermia treatment. Presented model takes into account not only the temperature distributions but also the thermal dose parameter. Obtaining of temperature distributions takes advantage of the generalized dual phase lag equation. For computer calculations the parallelized algorithm was prepared.

**Keywords:** artificial hyperthermia, finite difference method, parallelized calculations, dual phase lag model

## ANALIZA NUMERYCZNA ZABIEGU SZTUCZNEJ HIPERTERMII

**Streszczenie.** Artykuł dotyczy numerycznego modelowania zabiegu sztucznej hipertermii. Analiza skuteczności zabiegu jest rozpatrywana nie tylko na podstawie czasoprzestrzennych rozkładów temperatury, ale także w oparciu o parametr dawki termicznej. Do modelowania przepływu ciepła w rozpatrywanym obszarze wykorzystano uogólnione równanie z dwoma czasami opóźnień. Na potrzeby obliczeń numerycznych napisano autorski program oparty o obliczenia równoległe.

**Słowa kluczowe:** sztuczna hipertermia, metoda różnic skończonych, obliczenia równoległe, uogólnione równanie z dwoma czasami opóźnień

### Introduction

From the medical point of view hyperthermia is the sudden, rapid rise in a body temperature. Artificial hyperthermia is a treatment, in which the body temperature is purposefully raised, usually to 42 - 46 °C. There are three types of artificial hyperthermia: local, regional and whole-body. In this paper, only the local is considered. Local artificial hyperthermia is usually used as cancer treatment often associated with chemo - or radiotherapy. When this treatment is used unsupported, in cancer cells it causes lack of oxygen and nutrients, what leads to the apoptosis. Heat shock causes inducing of the heat shock proteins. Rise of temperature results in better blood supply to the organ and therefore drug accumulation. Chemical reactions are faster at higher temperatures. Artificial hyperthermia associated with the radiotherapy perpetuates damage of DNA.

It also should be noted, that the biological tissue is the material with particular nonhomogeneous inner structure and interwoven by blood vessels (Fig. 1). Sensitive influence on the temperature distribution has a volume of the blood vessels and blood velocity. The bioheat transfer process is multiscale, therefore it is necessary to consider delays of heat flux and temperature gradient [1].

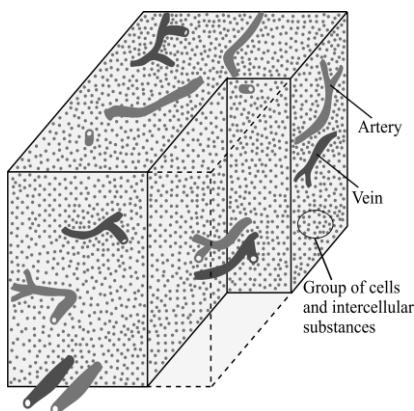


Fig. 1. Tissue model

To prevent damage of healthy tissue, as well heating the considered area to desirable temperature, the ability to predict the temperature distribution accurately, in a short calculation time is very important.

A model, which allows one to take into account the tissue porosity and phase lags depending on the parameters of tissue is the generalized dual phase lag model [11]. It should be pointed out that the comparison of various bioheat transfer models was done by authors in [8, 9].

It should be remembered that the degree of tissue destruction depends not only on the temperature, but also the exposure time and can be described mathematically by means of the thermal dose parameter [14].

### 1. Generalized dual phase lag equation

The tissue, as shown in figure 1, can be treated as a porous medium divided into two regions: the vascular region (blood vessel) and the extravascular region (tissue) [4, 11]. To describe temperature field in the heating regions (blood (1) and tissue (2)) the two-equation porous model [12] can be applied

$$(1-\varepsilon)\rho_t c_t \frac{\partial T_t}{\partial t} = (1-\varepsilon)\lambda_t \nabla^2 T_t + \alpha A(T_b - T_t) + \\ wc_b(T_b - T_t) + (1-\varepsilon)Q_{mt} + (1-\varepsilon)Q_{ex} \quad (1)$$

$$\varepsilon\rho_b c_b \left[ \frac{\partial T_b}{\partial t} + \mathbf{v} \cdot \nabla T_b \right] = \varepsilon\lambda_b \nabla^2 T_b + \alpha A(T_t - T_b) + \\ wc_b(T_t - T_b) + \varepsilon Q_{mb} + \varepsilon Q_{ex} \quad (2)$$

where  $\varepsilon$  denotes the porosity (the ratio of blood volume to the total volume),  $\alpha$  is the heat transfer coefficient,  $\mathbf{v}$  is the blood velocity,  $A$  is the volumetric transfer area between tissue and blood,  $c$  is the specific heat,  $\rho$  is the density,  $\lambda$  is the thermal conductivity,  $T$  denotes temperature,  $t$  is the time,  $w$  is the blood perfusion rate,  $Q_m$  is the metabolic heat source and  $Q_{ex}$  is the capacity of internal heat sources associated with the external heating of tissue [9] while subscripts  $t$  and  $b$  represent tissue and blood, respectively. Adding both (1) and (2) equations, the following equation can be obtain

$$\varepsilon\rho_b c_b \frac{\partial T_b}{\partial t} + (1-\varepsilon)\rho_t c_t \frac{\partial T_t}{\partial t} + \varepsilon\rho_b c_b \mathbf{v} \cdot \nabla T_b = \varepsilon\lambda_b \nabla^2 T_b \\ + (1-\varepsilon)\lambda_t \nabla^2 T_t + \varepsilon Q_{mb} + (1-\varepsilon)Q_{mt} + Q_{ex} \quad (3)$$

In this paper is assumed that the coupling factor is equal to  $G = A\alpha + wc_b$  and also that before reaching the equilibrium temperature of tissue and blood, the blood temperature changes according to the Minkowycz hypothesis [10]

$$\varepsilon\rho_b c_b \frac{\partial T_b}{\partial t} = G(T_t - T_b) \quad (4)$$

Based on (4) the temperature of tissue is described as follows

$$T_t = T_b + \frac{\varepsilon\rho_b c_b}{G} \frac{\partial T_b}{\partial t} \quad (5)$$

Using (5) and (3), after some mathematical operations the equation for blood temperature can be written in the form

$$\begin{aligned} & [\varepsilon \rho_b c_b + (1-\varepsilon) \rho_t c_t] \frac{\partial T_b}{\partial t} + (1-\varepsilon) \rho_t c_t \frac{\varepsilon \rho_b c_b}{G} \frac{\partial^2 T_b}{\partial t^2} + \varepsilon \rho_b c_b \mathbf{v} \cdot \nabla T_b \\ & = [\varepsilon \lambda_b + (1-\varepsilon) \lambda_t] \nabla^2 T_b + \frac{\varepsilon (1-\varepsilon) \lambda_t \rho_b c_b}{G} \frac{\partial}{\partial t} (\nabla^2 T_b) \\ & + \varepsilon Q_{mb} + (1-\varepsilon) Q_{mt} + Q_{ex} \end{aligned} \quad (6)$$

Now, the effectiveness parameters can be introduced:

$$\lambda_e = \varepsilon \lambda_b + (1-\varepsilon) \lambda_t \quad (7)$$

and

$$C_e = \varepsilon \rho_b c_b + (1-\varepsilon) \rho_t c_t \quad (8)$$

Assuming the following form of relaxation time and the thermalization time

$$\tau_q = \frac{\varepsilon (1-\varepsilon) \rho_t c_t \rho_b c_b}{G C_e} \quad (9)$$

$$\tau_T = \frac{\varepsilon (1-\varepsilon) \lambda_t \rho_b c_b}{G \lambda_e} \quad (10)$$

the equation (6) can be written as follows

$$\begin{aligned} & C_e \left( \frac{\partial T_b}{\partial t} + \tau_q \frac{\partial^2 T_b}{\partial t^2} \right) + \varepsilon \rho_b c_b \mathbf{V} \cdot \nabla T_b = \lambda_e \nabla^2 T_b \\ & + \lambda_e \tau_T \frac{\partial}{\partial t} (\nabla^2 T_b) + \varepsilon Q_{mb} + (1-\varepsilon) Q_{mt} + Q_{ex} \end{aligned} \quad (11)$$

In equation (11) the unknown is the blood temperature. To determine the equation where only unknown is the tissue temperature the dependence (5) should be transform

$$T_b = T_t - \frac{\varepsilon \rho_b c_b}{G} \frac{\partial T_b}{\partial t} \quad (12)$$

Based on (11), (12) and after some mathematical operations the equation for tissue temperature is described as follows

$$\begin{aligned} & C_e \left( \frac{\partial T_t}{\partial t} + \tau_q \frac{\partial^2 T_t}{\partial t^2} \right) = \lambda_e \nabla^2 T_t + \lambda_e \tau_T \frac{\partial}{\partial t} (\nabla^2 T_t) + \\ & G(T_b - T_t) + \varepsilon Q_{mb} + (1-\varepsilon) Q_{mt} + Q_{ex} \\ & \frac{\tau_q C_e}{(1-\varepsilon) \rho_t c_t} \left[ \varepsilon \frac{\partial Q_{mb}}{\partial t} + (1-\varepsilon) \frac{\partial Q_{mt}}{\partial t} + \frac{\partial Q_{ex}}{\partial t} \right] \end{aligned} \quad (13)$$

## 2. Concept of thermal dose

Knowledge of time – dependent temperature field during the thermal treatment allows one to determine the thermal dose  $TD$  in terms of equivalent minutes at temperature  $43^\circ\text{C}$ . In particular, the following equation should be taken into account [14]

$$TD = \int_{t^0}^{t^F} R^{43-T} dt = \sum_{f=1}^F R^{43-T^f} \Delta t \quad (14)$$

where  $t^0, t^F$  correspond to the initial and final times, respectively,  $T^f$  is the temperature at the point considered for time  $t^f$ ,  $\Delta t$  is the time step,  $R = 0$  for  $T \leq 39^\circ\text{C}$ ,  $R = 0.25$  for  $39^\circ\text{C} < T < 43^\circ\text{C}$ , and  $R = 0.5$  for  $T \geq 43^\circ\text{C}$ . The  $TD$  value required for total necrosis in a case of muscle tissue (this type of soft tissue is considered here) is equal to  $TD = 240$  minutes [14].

## 3. Formulation of the problem

Assumed model is shown in figure 2. The domain of healthy tissue  $\Omega_1$  is a cube with edge length of 0.05 m and centrally located subdomain of the tumor  $\Omega_2$  with edge length of 0.01 m. The considered domain includes the blood vessels arranged in the direction of the X axis.

The thermophysical parameters of tumor and healthy tissue are assumed to be the same, so only one equation describing the temperature field in domain  $\Omega = \Omega_1 \cup \Omega_2$  is considered. The external heating of tissue is a constant function

$$\begin{cases} (x, y, z) \in \Omega_1 : Q_{ex}(x, y, z, t) = 0 \\ (x, y, z) \in \Omega_2 : Q_{ex}(x, y, z, t) = \begin{cases} Q_0, & t \leq t_{ex} \\ 0, & t > t_{ex} \end{cases} \end{cases} \quad (15)$$

where  $Q_0$  is constant nonzero component and  $t_{ex}$  is duration of heating (exposure time).

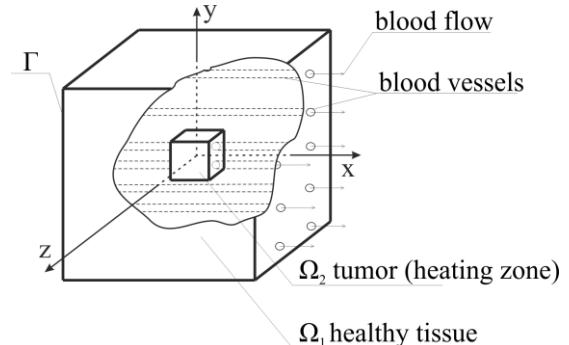


Fig. 2. Domain considered

## 4. Methods of solution

Assuming constant value of metabolic heat source and using formula (15) the equation (13) can be written in the form

$$\begin{aligned} & C_e \frac{\partial T_t}{\partial t} + C_e \tau_q \frac{\partial^2 T_t}{\partial t^2} = \lambda_e \nabla^2 T_t + \lambda_e \tau_T \frac{\partial}{\partial t} (\nabla^2 T_t) \\ & + G(T_b - T_t) + \varepsilon Q_{mb} + (1-\varepsilon) Q_{mt} + Q_{ex} \end{aligned} \quad (16)$$

This equation is supplemented by boundary condition

$$-\lambda n \cdot \nabla T_t(x, y, z, t) = 0 \quad (17)$$

where  $n$  is the normal outward vector [3]. The initial conditions are as follows

$$t = 0 : T_t(x, y, z, t) = T_p, \quad \frac{\partial T_t(x, y, z, t)}{\partial t} = 0 \quad (18)$$

where  $T_p$  is the initial temperature of tissue. Let  $T^f = T_t(x, y, z, f \Delta t)$  where  $\Delta t$  is the time step [7]. Then, for time  $t^f = f \Delta t$  ( $f \geq 2$ ) the following approximate form of equation (16) can be proposed

$$\begin{aligned} & \frac{C(\Delta t + \tau_q)}{(\Delta t)^2} T^f = \frac{C(\Delta t + 2\tau_q) - G(\Delta t)^2}{(\Delta t)^2} T^{f-1} \\ & - \frac{C\tau_q}{(\Delta t)^2} T^{f-2} + \frac{\lambda(\Delta t + \tau_T)}{\Delta t} \nabla^2 T^{f-1} - \frac{\lambda\tau_T}{\Delta t} \nabla^2 T^{f-2} \\ & + GT_b + \varepsilon Q_{mb} + (1-\varepsilon) Q_{mt} + Q_{ex} \end{aligned} \quad (19)$$

For simplification of notation the subscripts  $t$  and  $e$  are here omitted. The uniform grid of dimensions  $n \times n \times n$  is introduced and then the finite difference equation for internal node  $(i, j, k)$  has the following form [6]

$$\begin{aligned} & \frac{C(\Delta t + \tau_q)}{(\Delta t)^2} T_{i,j,k}^f = \frac{C(\Delta t + 2\tau_q) - G(\Delta t)^2}{(\Delta t)^2} T_{i,j,k}^{f-1} \\ & - \frac{C\tau_q}{(\Delta t)^2} T_{i,j,k}^{f-2} + \frac{\lambda(\Delta t + \tau_T)}{\Delta t} \nabla^2 T_{i,j,k}^{f-1} - \frac{\lambda\tau_T}{\Delta t} \nabla^2 T_{i,j,k}^{f-2} \\ & + GT_b + \varepsilon Q_{mb} + (1-\varepsilon) Q_{mt} + Q_{ex} \end{aligned} \quad (20)$$

where:

$$\begin{aligned} \nabla^2 T_{i,j,k}^s &= \frac{T_{i-1,j,k}^s - 2T_{i,j,k}^s + T_{i+1,j,k}^s}{h^2} \\ & + \frac{T_{i,j-1,k}^s - 2T_{i,j,k}^s + T_{i,j+1,k}^s}{h^2} + \frac{T_{i,j,k-1}^s - 2T_{i,j,k}^s + T_{i,j,k+1}^s}{h^2} \end{aligned} \quad (21)$$

while  $s = f - 1$  or  $s = f - 2$  and  $h$  is the constant grid step. Finally, the temperature at the node  $(i, j, k)$  is calculated from

$$\begin{aligned} T_{i,j,k}^f &= \frac{Ch^2(\Delta t + 2\tau_q) - Gh^2(\Delta t)^2 - 6\lambda\Delta t(\Delta t + \tau_T)}{Ch^2(\Delta t + \tau_q)} T_{i,j,k}^{f-1} \\ &+ \frac{(\Delta t)^2 [GT_b + \varepsilon Q_{mb} + (1 - \varepsilon)Q_{mt} + Q_{ex}]}{C(\Delta t + \tau_q)} \\ &+ \frac{\lambda\Delta t(\Delta t + \tau_T) \cdot dev1 - \lambda\Delta t\tau_T \cdot dev2 - (Ch^2\tau_q - 6\lambda\Delta t\tau_T)T_{i,j,k}^{f-2}}{Ch^2(\Delta t + \tau_q)} \end{aligned} \quad (22)$$

where

$$\begin{aligned} dev1 &= (T_{i-1,j,k}^{f-1} + T_{i+1,j,k}^{f-1} + T_{i,j-1,k}^{f-1} + T_{i,j+1,k}^{f-1} + T_{i,j,k-1}^{f-1} + T_{i,j,k+1}^{f-1}) \\ dev2 &= (T_{i-1,j,k}^{f-2} + T_{i+1,j,k}^{f-2} + T_{i,j-1,k}^{f-2} + T_{i,j+1,k}^{f-2} + T_{i,j,k-1}^{f-2} + T_{i,j,k+1}^{f-2}) \end{aligned} \quad (23)$$

It should be pointed out that in the case of explicit scheme application a criterion of stability should be formulated. The solving system is stable if the coefficients in the difference equations (22) for time  $t^{f-1}$  are non-negative. Hence it results that the following coefficient must be positive

$$\frac{Ch^2(\Delta t + 2\tau_q) - Gh^2(\Delta t)^2 - 6\lambda\Delta t(\Delta t + \tau_T)}{Ch^2(\Delta t + \tau_q)} \geq 0 \quad (22)$$

## 5. CPU parallel algorithm

All the time steps must be performed consecutively so the time loop can't be divided into the parallel calculation. Temperature calculations at all nodes in each time step are executed in three nested loops: in the  $x$  direction, in the  $y$  direction and in the  $z$  direction. These calculations can be easily divided into the parallel because all temperatures at the points are calculated based on the  $f - 1$  and  $f - 2$  time steps. In figure 3 the example of parallelization of CPU calculations is shown. The number of threads "q" depends on the CPU cores.

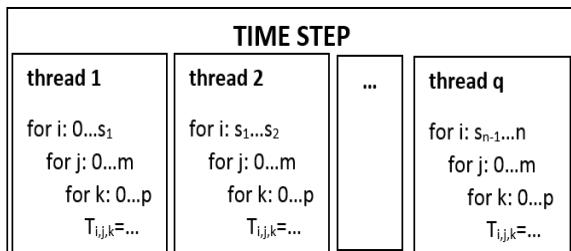


Fig. 3. CPU parallelization of calculations

## 6. GPU parallel algorithm

To achieve acceleration of computing time the CUDA technology of NVidia was implemented in computer program. This platform allows to use the graphics processing unit (GPU) for scientific computing. Unlike the CPU, the graphics processor is made up of hundreds of thousands cores (Fig. 4). Each of these cores may perform calculations independently.

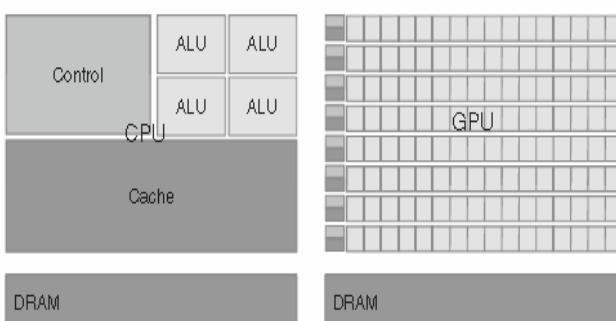


Fig. 4. Model of CPU and GPU [5]

The main limitation of graphics cards is the speed of copying data from the host to the device and the access time to data in the memory. The idea of using the GPU to accelerate the calculations associated with the finite difference method application is based on the fact that in each successive time steps the calculated data are new data for next time step, so it is not necessary to copy these data from the host to the device. The program algorithm is presented in figure 5.

The next very important factor which has major impact on application efficiency is the idea of using shared memory. The global memory of the device has long access latencies and finite access bandwidth. Unlike to the previously, shared memory can be accessed at very high speed. The biggest problem in use of shared memory is limited amount of this memory [13].

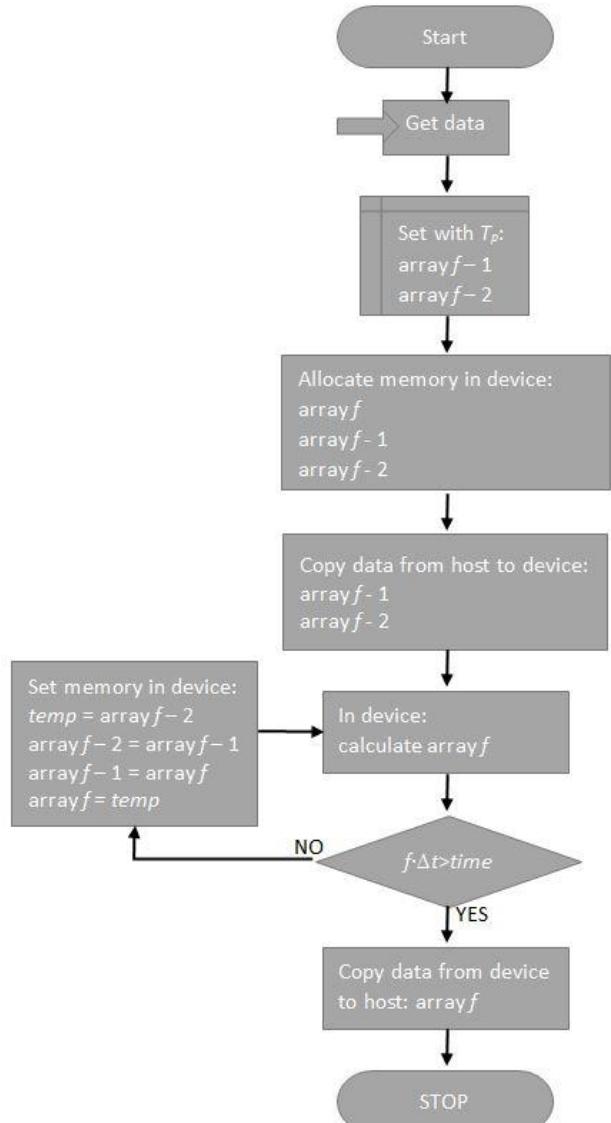


Fig. 5. Algorithm

Data for time steps  $f, f - 1$  and  $f - 2$  are stored in the memory as one dimensional arrays. In chosen approach each thread block loads a tile of data from those arrays. Proper choice of tile dimensions required some experiments. It was decided to use a  $4 \times 4 \times 25$  block size. Then for calculating all nodes temperature, the two arrays, in each threads blocks, from previous time steps of size  $6 \times 6 \times 27$  are required (fig. 6).

The part of the code of the device kernel function, which copies the data from the global to the shared memory and calculates node temperature is shown on figure 7. After determining the temperature, for every node the thermal dose was also calculated.

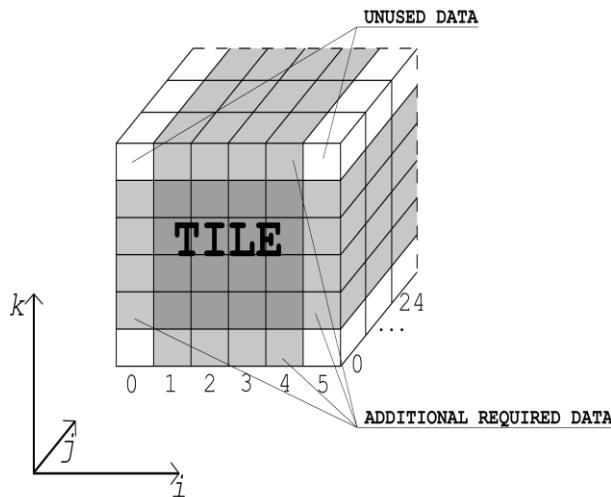


Fig. 6. Array of data from f-1 time step in shared memory

```

__global__ void TimeStepKernel(float
*arrF, const float
    *arrF1, const float *arrF2,
    Args arg)
{
    __shared__ float sF1[6][6][27];
    __shared__ float sF2[6][6][27];
int dimI = arg.dimI;
int dimJ = arg.dimJ;
int dimK = arg.dimK;
int tx = threadIdx.x;
int ty = threadIdx.y;
int tz = threadIdx.z;
int i = blockDim.x * blockIdx.x + tx;
int j = blockDim.y * blockIdx.y + ty;
int k = tz + arg.shift;

...
...

sF1[tx+1][ty+1][tz+1] =
arrF1[i*dimJ*dimK+j*dimK+k];
sF2[tx+1][ty+1][tz+1] =
arrF2[i*dimJ*dimK+j*dimK+k];
__syncthreads();

arrF[i*dimJ*dimK+j*dimK+k] =
    arg.A * sF1[tx+1][ty+1][tz+1] + arg.B
*
    (sF1[tx][ty+1][tz+1] +
sF1[tx+2][ty+1][tz+1] +
    sF1[tx+1][ty][tz+1] +
sF1[tx+1][ty+2][tz+1] +
    sF1[tx+1][ty+1][tz] +
sF1[tx+1][ty+1][tz+2]) -
    arg.C * (sF2[tx][ty+1][tz+1] +
sF2[tx+2][ty+1][tz+1] +
    sF2[tx+1][ty][tz+1] +
sF2[tx+1][ty+2][tz+1] +
    sF2[tx+1][ty+1][tz] +
sF2[tx+1][ty+1][tz+2]) - arg.D *
    sF2[tx+1][ty+1][tz+1] + arg.F + arg.E
* Qe;
__syncthreads();
}

```

Fig. 7. Device kernel function

## 7. Results

In numerical computations the following values of parameters have been assumed: thermal conductivity of blood  $\lambda_b$ , thermal conductivity of tissue  $\lambda_t = 0.5 \text{ W/(mK)}$ , blood density  $\rho_b = 1060 \text{ kg/m}^3$ , tissue density  $\rho_t = 1000 \text{ kg/m}^3$ , specific heat capacity of blood  $c_b = 3770 \text{ J/(kgK)}$ , specific heat capacity of tissue  $c_t = 4000 \text{ J/(kgK)}$ , metabolic heat source (of tissue and blood)  $Q_{mb} = Q_{mt} = 250 \text{ W/m}^3$ , blood temperature  $T_b = 37^\circ\text{C}$ , initial temperature  $T_p = 37^\circ\text{C}$ , porosity  $\epsilon = 0.0137$  and  $G = 27097.8 \text{ W/(m}^3\text{ K)}$ . The values of phase lag times  $\tau_q$  and  $\tau_T$  were determined using formulas (9) and (10). The spatial discretization creates  $500 \times 500 \times 500$  nodes and time step is equal to  $\Delta t = 0.01 \text{ s}$ . Following heating condition have been taken into account [9]: 35 s heating with a power density of  $1 \text{ MW/m}^3$ .

The program has been running on a computer with the processor Intel Core i7-3960X and the graphic card GeForce GTX 680. The processor has the six cores, each with two threads and the clock speed 3.3 GHz. The graphics processing unit has 1536 CUDA cores with base clock 1006 MHz and 2048 MB of global memory.

In figure 8 the temperature history at the central node of cube is presented. One can see that in the cube the maximum temperature  $44^\circ\text{C}$ . occurs and the temperature above  $43^\circ\text{C}$  is maintained only by 18 seconds.

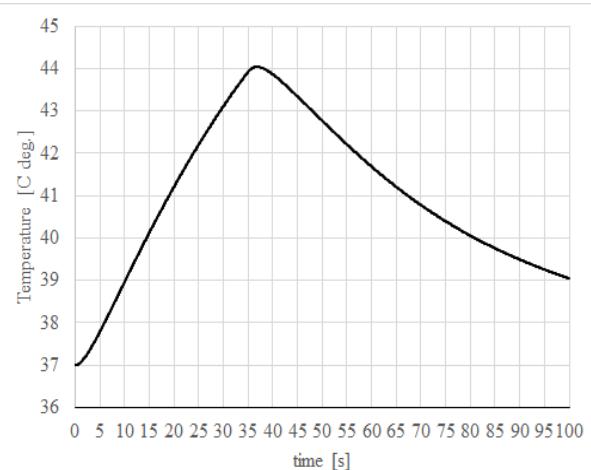


Fig. 8. Temperature history at central node of cube

Figure 9 illustrates the temperature distribution at the cross section ( $z = 0$ ) after 10 second. The temperature above  $37^\circ\text{C}$  is just inside the tumor region.

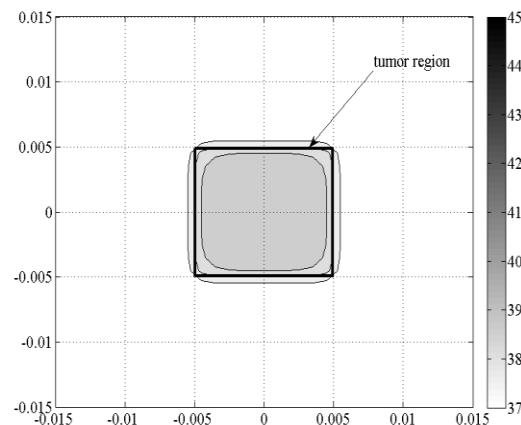


Fig. 9. Temperature distribution at the central part of cross section after 10s

In Figure 10 the temperature distribution in the cross section of the cube after 35 second is shown. In healthy tissue the temperature above 37°C appeared.

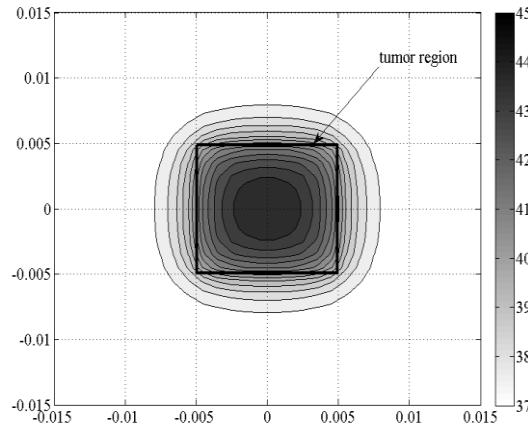


Fig. 10. Temperature distribution at the central part of cross section after 35s

After 60 seconds the temperature began to decrease – figure 11, but in the healthy tissue, there is still the temperature above 37°C. Also, more of the area  $\Omega_1$  is occupied by the elevated temperature.

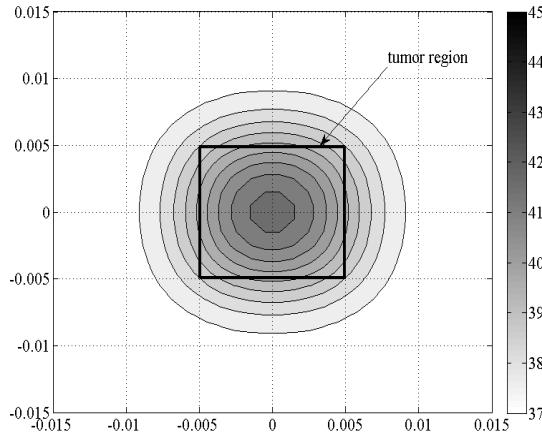


Fig. 11. Temperature distribution at the central part of cross section after 60s

After 100 seconds the temperature in the entire domain is less than 39°C (figure 12).

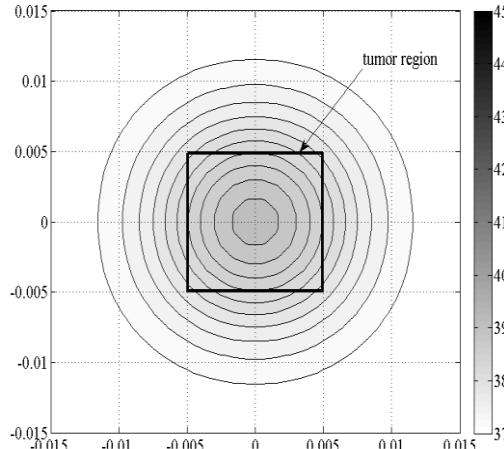


Fig. 12. Temperature distribution at the central part of cross section after 100s

In figure 13 the thermal dose history at the central node of the cube is presented. It is clearly that TD rise is meaningful in time from 25 to 60 seconds. After this time the thermal dose rise a little. It should be noted that values of thermal dose do not exceed 240 minutes.

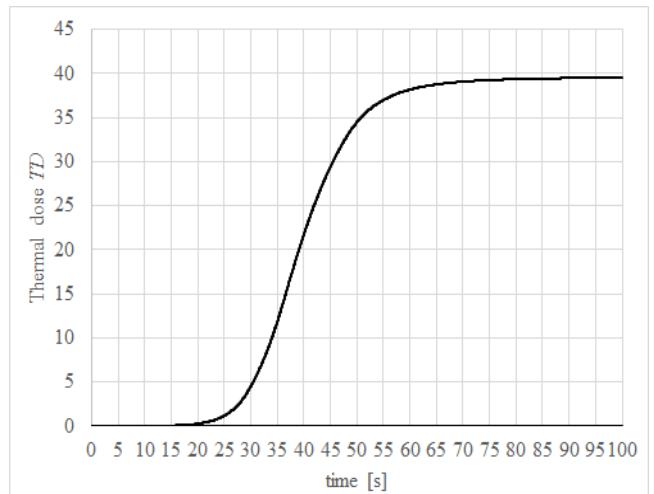


Fig. 13. Thermal dose history at central node of cube

In figure 14 the distribution of thermal dose in the central cross section is presented. It can be seen that all elevated values are inside the region  $\Omega_2$ .

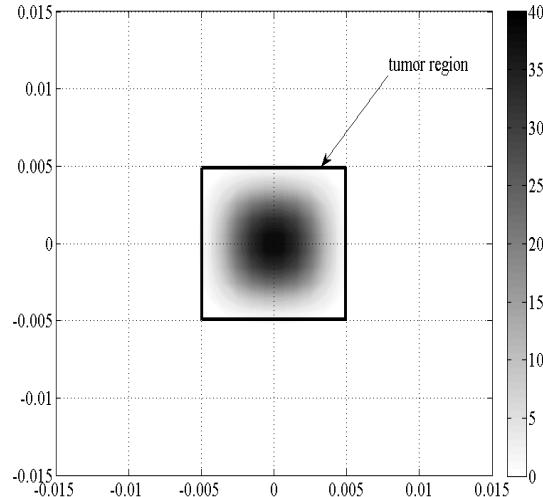


Fig. 14. Thermal dose distribution at the central part of cross section after 60s

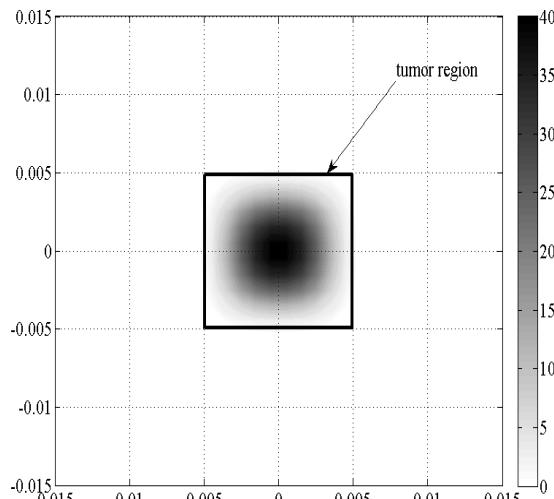


Fig. 15. Thermal dose distribution at the central part of cross section after 100s

Most important thermal dose distribution is after 100s because then the temperature decreases under 39°C and then the coefficient  $R$  in the thermal dose concept is equal to zero.

This distribution is presented in figure 15. It should be emphasized that all values of  $TD$  above 0 minutes are still inside the tumor region. This means that the healthy tissue is heated, but it does not receive a significant thermal dose.

As previously mentioned, the time step is equal to  $\Delta t = 0.01$ s, while the analysis time is equal to 100s. Thus, the amount of time steps is equal to 10,000. Assumed number of nodes is equal to  $500 \times 500 \times 500$ , so the number of temperatures which is necessary to calculate in each time step is equal to 125,000,000.

Computer program, which used only the CPU, all the calculations has been performed during 37 minutes and 43 seconds, at 95% of CPU utilization (Fig. 16).

Computer program which used not only CPU but also GPU, the same calculations has been performed during 14 minutes and 1 second. As can be seen, the acceleration of calculations is very significant.

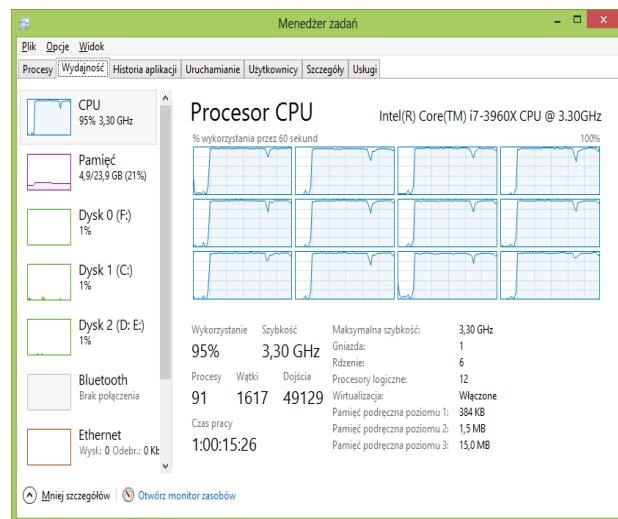


Fig. 16. CPU utilization (without using CUDA)

Table 1 provides a comparison of calculation times for different spatial discretizations. In all variants the same time step has been assumed. When changing the discretization for  $100 \times 100 \times 100$  the tile sizes also have to be changed ( $2 \times 2 \times 25$ ), of course. The maximum difference between the results of the GPU and CPU calculations was below  $1.6 \cdot 10^{-9}$ .

Table 1. Times of calculations

Spatial discretization	Calculation time		Acceleration CPU / GPU
	GPU	CPU	
$500 \times 500 \times 500$	14min 1s	37min 43s	2,7
$100 \times 100 \times 100$	8 s	21 s	2,5
$50 \times 50 \times 50$	2,6	6,4	2,46

## 8. Results

In this paper the bioheat transfer process in three dimensional domain including the healthy tissue and the tumor region has been considered. Some simplifications were adopted, for example: very regular tumor shape and heating only in domain  $\Omega_2$ .

As can be seen in figures 9 – 12, the temperatures above  $37^\circ\text{C}$ . occur not only in the tumor, but also in the area of healthy tissue. During the treatment it is very important to prevent damage of healthy tissue and to provide adequate thermal dose in the tumor region. For a patient, the long duration of heating at high temperature will induce a feeling of discomfort and pain [8]. Based on the received thermal dose distribution it can be seen that not only the temperature is important, but also the exposure time. Figures 14 and 15 show that the thermal dose values above zero minutes are cumulated inside domain  $\Omega_2$ .

Using CUDA platform significantly speeds up the calculations. Calculations on graphics processing units should be implemented to the program, which repeatedly performs the complex analysis.

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## ANALIZA ZAKŁÓCEŃ W SIECIACH ELEKTROENERGETYCZNYCH WYWOLANYCH WYŁADOWANIAMI PIORUNOWYMI

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**Streszczenie.** W artykule przedstawiono złożoność problematyki analizy stanów nieustalonych napięć pojawiających się w układzie elektroenergetycznym wskutek bezpośrednich wyładowań piorunowych do elementów konstrukcyjnych linii napowietrznej. Analiza zakłóceń eksplotacyjnych wywołanych wyładowaniami piorunowymi dotyczy układu elektroenergetycznego o napięciu znamionowym 110 kV. Przedstawione wyniki stanowią przykład analizy narządów napięciowych układów izolacyjnych aparatów stacyjnych z uwzględnieniem różnych wariantów zastosowanej ochrony przepięciowej w analizowanej stacji. Symulacje opisywanego zakłócenia zostały dokonane przy pomocy programu The Electromagnetic Transients Program - Alternative Transients Program (EMTP-ATP).

**Słowa kluczowe:** zakłócenia, efekty falowe, wyładowania piorunowe, EMTP-ATP

### ANALYSIS OF DISTURBANCES IN ELECTRIC POWERS SYSTEMS CAUSED BY LIGHTNING DISCHARGES

**Abstract.** This paper deals with analyzing specific transient states of voltages in electric power systems of high voltages. The paper presents the results of the analysis of operational disturbances caused by lightning discharges in 110 kV power system. Furthermore, the analysis results of lightning surges as well as the optimization results of a surge protection system installed in a 110 kV substation are presented. A model of an electric power system (overhead lines and substation) and all simulations were performed using computer software Electromagnetic Transients Program-Alternative Transients Program (EMTP-ATP). This model is based on a set of appropriately connected elements (distributed and lumped parameter elements) taking wave effects and nonlinear effects into consideration.

**Keywords:** disturbances, travelling waves, lightning discharges, EMTP-ATP

### Wstęp

W systemie elektroenergetycznym występują zakłócenia eksplotacyjne, mogące doprowadzić do uszkodzenia zainstalowanych w nim aparatów i urządzeń. Jednym z zakłóceń są przepięcia, będące niezamierzonymi eksplotacyjnie wzrostami napięć powyżej najwyższych dopuszczalnych napięć roboczych. Mogą one prowadzić do degradacji lub uszkodzenia układów izolacyjnych urządzeń.

Najistotniejszymi z punktu widzenia zagrożeń układów izolacyjnych są przepięcia wywołane przez wyładowania piorunowe. Charakteryzują się one krótkim czasem trwania (rzędu kilkuset mikrosekund), dużymi wartościami szczytowymi (dochodzącymi do kilku megawoltów) oraz znacznymi stromościami narastania (rzędu kilku megawoltów na mikrosekundę).

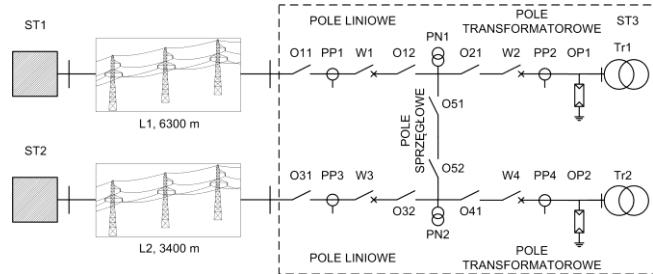
Przepięcia atmosferyczne powstawać mogą zarówno jako efekt indukcji elektromagnetycznej wywołanej przepływem prądu w kanale pioruna, jak również jako skutek bezpośrednich uderzeń pioruna do obiektów elektroenergetycznych. Stosowana w stacjach elektroenergetycznych ochrona odgromowa powoduje, że bezpośrednie uderzenie pioruna do urządzeń stacyjnych jest niemożliwe. Również linie wysokich i najwyższych napięć wyposaża się w ochronę w postaci przewodów odgromowych.

Ochrona odgromowa linii nie jest całkowicie niezawodna, a tym samym możliwe jest uderzenie pioruna w przewód fazowy i powstanie fali udarowej napięcia, stanowiącej zagrożenie nie tylko dla izolacji linii, ale również przyłączonych do niej stacji. O poziomie przepięć atmosferycznych decydują warunki ich powstawania w linii, a także efekty falowe wewnętrz stacji oraz zastosowane środki ochrony przeciwprzepięciowej. Jeżeli wyładowanie piorunowe zostanie przechwycone przez przewody odgromowe linii, to istnieje ryzyko, że w niesprzyjających warunkach nastąpi utrata wytrzymałości elektrycznej układu izolacyjnego, nazywana przeskokiem odwrotnym.

W artykule przedstawiono analizę pewnego zakłócenia w sieci 110 kV wywołanego wyładowaniami piorunowymi do linii zasilającej stację elektroenergetyczną. Konsekwencją tego zdarzenia było uszkodzenie aparatury stacyjnej. W celu dokonania analizy omawianego zakłócenia opracowano w programie EMTP-ATP model fragmentu sieci elektroenergetycznej. Opracowany model uwzględnia istotne z punktu widzenia prowadzonej analizy zjawiska fizyczne zachodzące w analizowanym układzie.

### 1. Opis analizowanego zakłócenia

Przedmiotem analizy jest sieć o napięciu 110 kV, której schemat przedstawiono na rysunku 1. W sieci tej znajduje się stacja 110 kV/SN (ST3) zasilana dwoma jednotorowymi liniami 110 kV (L1, L2) ze stacji ST1 i ST2.



Rys. 1. Schemat rozpatrywanego układu sieci 110 kV (ST - stacja elektroenergetyczna, L - linia napowietrzna, O - odłącznik, PP - przekładnik prądowy, PN - przekładnik napięciowy, W - wyłącznik, OP - ogranicznik przepięć, Tr - transformator)

W analizowanym układzie sieci 110 kV doszło do złożonego zakłócenia będącego konsekwencją bezpośrednich wyładowań piorunowych do elementów konstrukcyjnych linii napowietrznej L2. Efektem opisywanego zakłócenia było uszkodzenie wyłącznika W3 znajdującego się w polu liniowym stacji ST3.

Odtworzenie możliwego scenariusza zaistniałego zakłócenia było możliwe na podstawie zarejestrowanych przebiegów prądów i napięć w stacjach, do których przyłączona jest linia L2. W czasie opisywanych zakłóceń w okolicy panowała burza z licznymi wyładowaniami piorunowymi, które niewątpliwie przyczyniły się do powstania omawianego zakłócenia – potwierdzają to wyniki rejestracji systemu automatycznej detekcji wyładowań piorunowych (LIMET).

Na wskutek wyładowania piorunowego do linii elektroenergetycznej L2 doszło w niej do zakłócenia w postaci zwarcia jednofazowego. Zakłócenie to zostało wyeliminowane poprzez zadziałanie automatyki zabezpieczeniowej przez obustronne wyłączenie linii w stacjach ST2 i ST3. Po około 170 ms od tego zakłócenia, doszło do ponownego uderzenia pioruna w linie L2, w konsekwencji którego doszło do uszkodzenia aparatury stacyjnej w stacji ST3.

## 2. Model analizowanej sieci elektroenergetycznej

W celu analizy zakłócenia przedstawionego w rozdziale 1 opracowano w programie EMTP-ATP model systemu 110 kV, przedstawiony na rysunku 1. Model ten złożony jest z modeli cząstkowych odzwierciedlających właściwości poszczególnych elementów konstrukcyjnych oraz istotne z punktu widzenia prowadzonej analizy zjawiska fizyczne zachodzące w analizowanym układzie [4, 5, 7, 8]. Model składa się z dwóch zasadniczych części: 1) modelu linii L1 i L2; 2) modelu rozdzielni 110 kV.

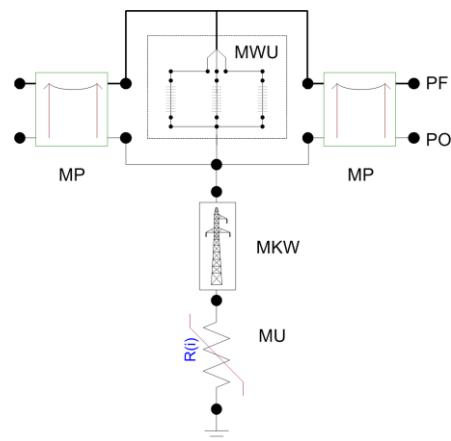
Linie napowietrzne odwzorowano jako zbiór szeregowo połączonych modeli cząstkowych. Uwzględniają one zasadnicze zjawiska zachodzące podczas wyładowania piorunowego do linii. Fragment modelu linii przedstawiono na rysunku 2. Wyróżnić w nim można modele przesła linii oraz modele zjawisk zachodzących w konstrukcjach wsporczych.

Model przesła linii (elementy MP na rysunku 2) odwzorowano w programie EMTP-ATP jako wieloprzewodowe linie długie o parametrach zależnych od częstotliwości. W modelu konstrukcji wsporczej uwzględniono trzy istotne zjawiska: efekty falowe w konstrukcji wsporczej, zjawiska nieliniowe w uziomie słupa oraz wytrzymałość udarowa izolacji linii. Model konstrukcji wsporczej zawiera więc trzy elementy (rysunek 2) [1, 7, 8]:

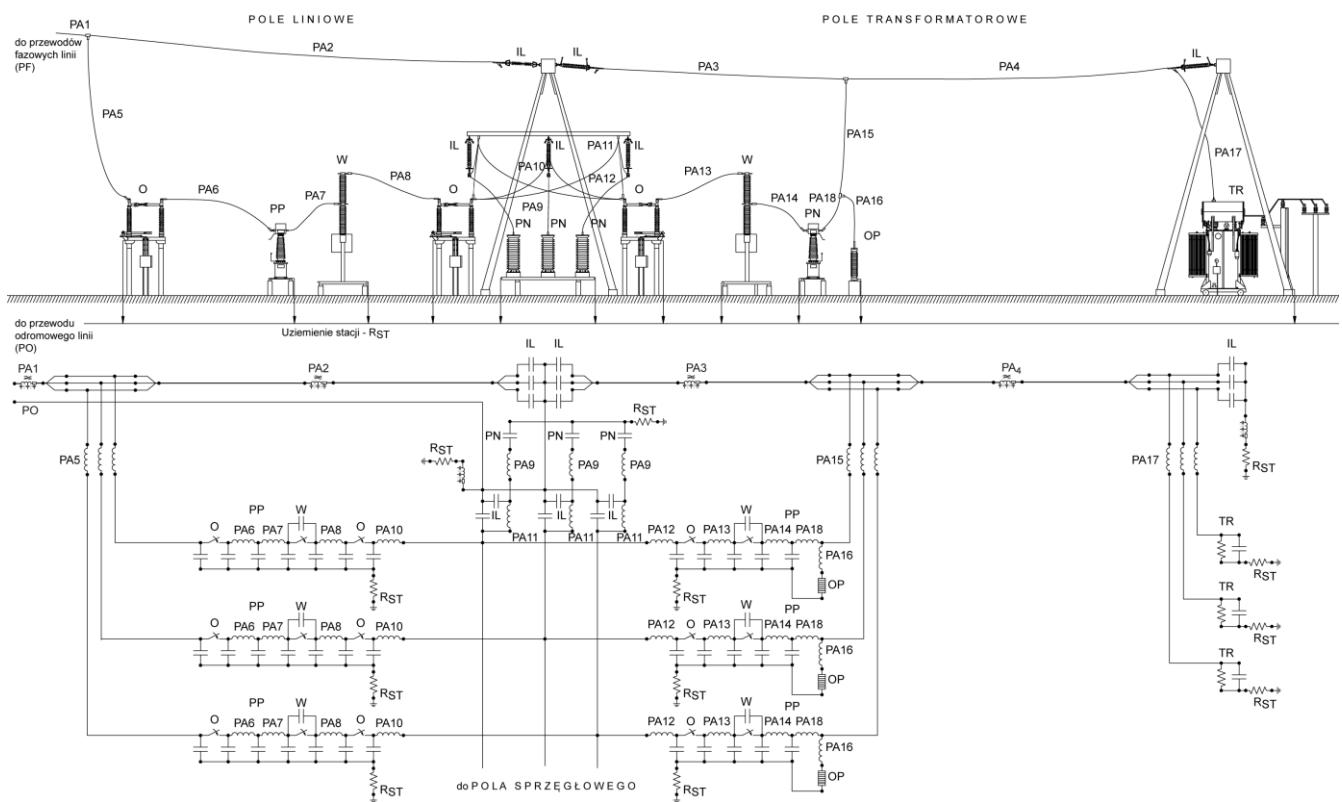
- element MKW stanowiący model zjawisk falowych w konstrukcji wsporczej, odwzorowany jako jednoprzewodowa bezstratna linia dłuża;
- element MU stanowiący model uziomu konstrukcji wsporczej podczas przepływu prądu pioruna, który odwzorowano w oparciu o wytyczne CIGRE i IEEE;
- element MWU stanowiący model wytrzymałości udarowej izolacji linii napowietrznej; model ten opracowano w oparciu o metodę rozwoju lidera LDM.

Stację elektroenergetyczną odwzorowano jako zbiór elementów odzwierciedlających poszczególne aparaty i urządzenia elektroenergetyczne, stanowiące wyposażenie stacji.

Fragment modelu stacji elektroenergetycznej, wykonany przy użyciu programu EMTP-ATP, został przedstawiony na rysunku 3. Model stacji elektroenergetycznej opracowano w oparciu o następujące założenia [2, 8]: przewody łączące (do 15 m długości) odwzorowano jako indukcyjność o wartości 1  $\mu\text{H}/\text{m}$ , przewody łączące (ponad 15 m długości) odwzorowano je jako modele linii wieloprzewodowej o parametrach rozłożonych, pojemności doziemne zainstalowanych urządzeń odwzorowano jako pojemności o wartościach z zakresu 100  $\text{pF}$  – 1  $\text{nF}$ , transformatory przedstawiono jako równolegle połączoną pojemność i rezystancję. Istotnym elementem jest model ograniczników przepięć. Dla przepięć atmosferycznych, model ogranicznika powinien uwzględniać zjawiska fizyczne zachodzące w strukturze waristorów. Modelem, który ma zastosowanie w analizie przepięć atmosferycznych, jest między innymi model proponowany przez IEEE [9].



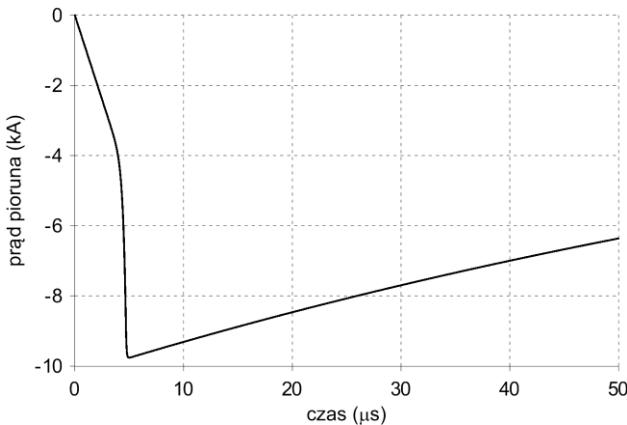
Rys. 2. Fragment modelu linii napowietrznej wykorzystany w badaniach symulacyjnych (PF – przewód fazowy, PO – przewód odgromowy, MP – model przesła, MWU – model wytrzymałości udarowej izolacji, MKW – model konstrukcji wsporczej, MU – model uziomu)



Rys. 3. Fragment modelu stacji elektroenergetycznej wykorzystany w badaniach symulacyjnych (O – odłącznik, PP – przekładnik prądowy, PN – przekładnik napięciowy, W – wylotnik, OP – ogranicznik przepięć, TR – transformator, IL – izolator liniowy, PA – połączenia międzymurowe)

### 3. Wyniki przeprowadzonej analizy

Opracowany model sieci 110 kV stał się podstawą analizy narażeń eksplotacyjnych wywołanych wyładowaniami piorunowymi do linii zasilającej stację. Podczas badań symulacyjnych wykorzystano model prądu pioruna o kształcie przedstawionym na rysunku 4. Model ten został odwzorowany za pomocą źródła prądu o wklęszym czołem i zmiennej wartości maksymalnej.



Rys. 4. Model kształtu prądu pioruna wykorzystany w badaniach symulacyjnych

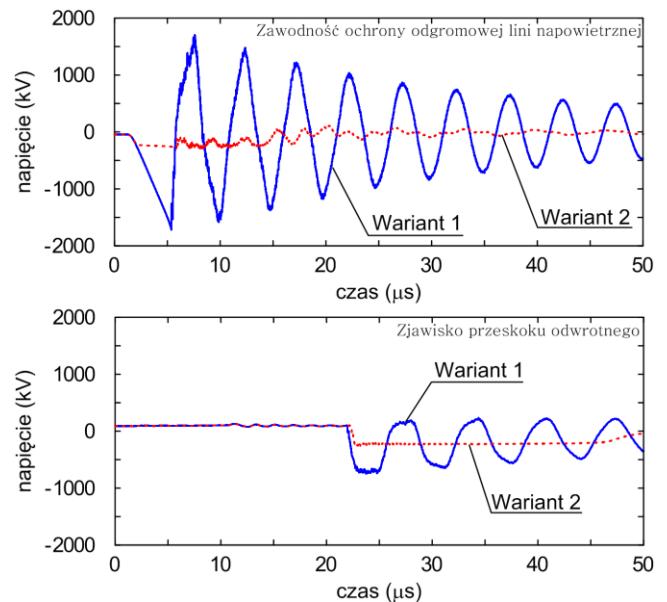
Celem przeprowadzonych symulacji była ocena poziomu przepięć w stacji elektroenergetycznej 110 kV, wywołanych bezpośrednim wyładowaniem piorunowym do linii napowietrznej L2. Przyjęto następujące założenia:

- przepięcia docierające do stacji wywołane są wyładowaniami piorunowymi do linii napowietrznej L2;
- w myśl teorii elektrogeometrycznej [5] możliwe jest uderzenie pioruna w przewód fazowy linii, jeżeli wartość szczytowa jego prądu jest mniejsza od wartości krytycznej; przeprowadzona analiza wykazała, że wartość ta wynosi 9,79 kA;
- przy wyładowaniach pioruna do słupów lub przewodów ogromowych możliwe jest wystąpienie przeskoku odwrotnego [3, 6, 7] będącego przyczyną przepięć w stacji; Przeprowadzona analiza wykazała, że krytyczna wartość szczytowa prądu powyżej której zjawisko to występuje wynosi 116,5 kA;
- wyładowanie piorunowe do linii L2 jest w odległości 350 m od stacji ST3.
- w analizie uwzględnia się najmniej korzystny wpływ przemiennego napięcia roboczego linii 110 kV;
- nieliniowe właściwości uziemienia konstrukcji wsporczej odwzorowano przy pomocy nieliniowej rezystancji o charakterystyce wyznaczonej na podstawie wartości rezystywności gruntu  $\rho = 300 \Omega\text{m}$  i rezystancji statycznej uziemienia  $R_T = 10 \Omega$  [1,2].
- obliczenia przeprowadzono dla wartości rezystancji uziemienia stacji  $R_{ST} = 0,56 \Omega$ ;
- analiza dotyczy stanu rozdzielnicy po zadziałaniu automatyki zabezpieczeniowej w wyniku zaistniałego zakłócenia przedstawionego w rozdziale II (otwarty wyłącznik W3 w polu liniowym stacji ST3).

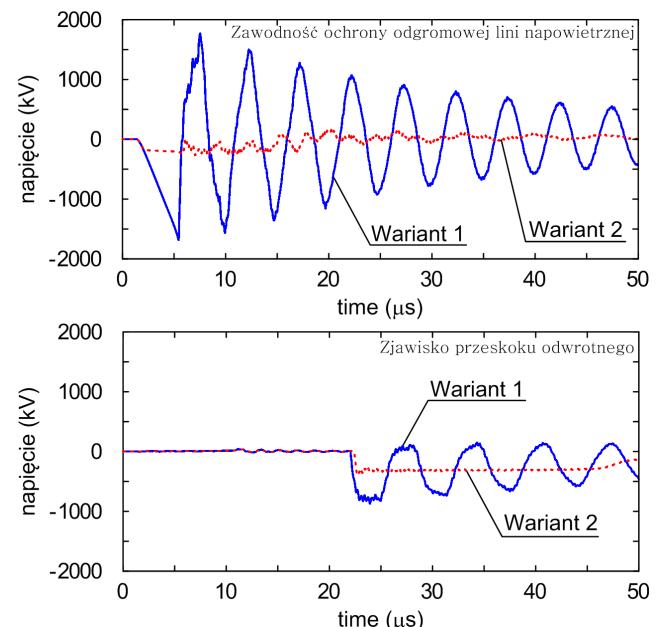
Celem analizy było wyznaczenie przepięć w charakterystycznych miejscach rozdzielnicy:

- w punkcie przyłączenia linii L2 do rozdzielnicy ST3;
- na stykach otwartego wyłącznika W3;
- na zaciskach transformatora Tr2.
- Rozważono dwa warianty ochrony przeciwprzepięciowej:
- wariant 1: ograniczniki przepięć zainstalowane są tylko w polach transformatorowych stacji (wariant istniejący);
- wariant 2: ograniczniki przepięć zainstalowane są w polach liniowych i transformatorowych stacji.

Na rysunkach 5-7 przedstawiono wybrane przebiegi czasowe przepięć w charakterystycznych punktach rozdzielnicy. Pokazuję one złożone zjawiska falowe zachodzące wewnętrz rozdzielnicy. Na kształt i wartości szczytowe przepięć wpływa wiele czynników, przy czym najistotniejszym z nich jest zastosowana ochrona przepięciowa. Zainstalowanie ograniczników przepięć tylko w polach transformatorowych powoduje obniżenie przepięć na zaciskach transformatora, lecz jednocześnie skutkuje znaczącą intensyfikacją przepięć w pozostałych miejscach rozdzielnicy – rysunek 8. Z tego powodu bezwzględnie wymagane jest również zastosowanie ograniczników w polach liniowych.



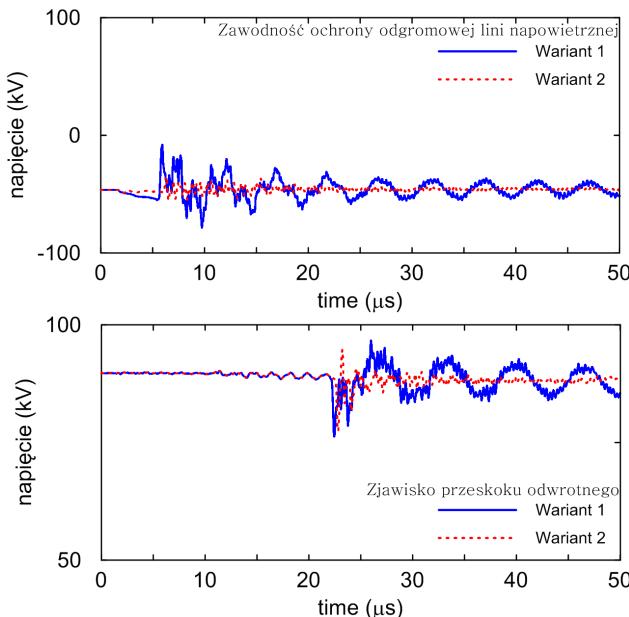
Rys. 5. Zarejestrowane przebiegi czasowe napięcia w polu liniowym stacji ST3



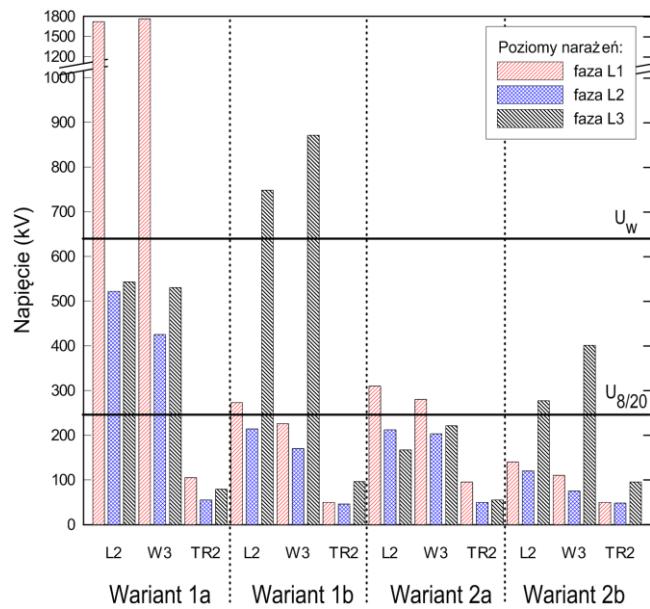
Rys. 6. Zarejestrowane przebiegi czasowe napięcia na stykach otwartego wyłącznika W3 w polu liniowym stacji ST3

Z przedstawionych na rysunku 8 wartości szczytowych przepięć wynika, że przy zastosowaniu ograniczników przepięć tylko w polach transformatorowych, możliwe jest wystąpienie na zaciskach otwartego wyłącznika W3 przepięć o wartościach szczytowych znacznie przekraczających wytrzymałość udarową piorunową wyłącznika wynoszącą 550 kV. Może to skutkować

przebiciem przerwy międzystykowej wyłącznika W3, a w efekcie prowadzić do podania napięcia roboczego od strony rozdzielni ST1 na zwarcie powstałe w wyniku uderzenia pioruna do linii L2. Konsekwencją tego może być przepływ prądu zwarciowego i uszkodzenie wyłącznika W3. Można więc sformułować wniosek, że przyczyną uszkodzenia wyłącznika W3 był brak właściwej ochrony przepięciowej rozdzielni ST3.



Rys. 7. Zarejestrowane przebiegi czasowe napięcia na zaciskach transformatora TR2 w stacji ST3



Rys. 8. Poziomy narażeń napięciowych w wybranych punktach stacji ST3 ( $U_W$  – wytrzymywane napięcie ударowe izolacji wyłącznika W3,  $U_{8/20}$  – napięcie obniżone ogranicznika przepięć dla prądu wyładowczego 10 kA i kształcie 8/20  $\mu$ s; wariant 1a, 2a – zawodność ochrony odgromowej linii; wariant 1b, 2b – przeskok odwrotny)

#### 4. Podsumowanie i wnioski

Bezpośrednie wyładowania piorunowe w przewód fazowy linii napowietrznej, a także przeskok odwrotny, mogą stanowić źródło przepięć o znacznych wartościach szczytowych. Szczególnie groźnym przypadkiem jest sytuacja, w której nie stosuje się ograniczników przepięć w polach liniowych stacji. Pojawiają się wówczas przepięcia, których wartości mogą znacznie przekraczać udarową wytrzymałość izolacji stosowanych urządzeń.

Z analizy narażeń przepięciowych rozpatrywanej sieci 110 kV wynika, że najbardziej prawdopodobną przyczyną uszkodzenia zainstalowanego w tej rozdzielni wyłącznika był brak właściwej ochrony przepięciowej rozdzielni.

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# IPv6 PROTOCOL - CHARACTERISTICS AND SUGGESTED METHODS OF IMPLEMENTATION IN EXISTING IPv4 NETWORKS USING CISCO ROUTERS

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**Abstract.** The article constitutes an introduction to IPv6 protocol and is a review of the existing approaches to ensure the coexistence of IPv6 and IPv4, on the example of homogeneous Cisco network infrastructure. In the first paragraph, the IPv6 protocol has been characterized and compared to the IPv4. Then, concepts connected with IPv6 addressing have been described. As the main part, it has been discussed methods to provide the coexistence of the two IP protocols. It has been characterized the primary option which is the dual stack, two types of both point to point and multipoint tunnels and finally - address translation NAT-PT.

**Keywords:** computer networks, IP networks, protocols

## PROTOKÓŁ IPv6 - CHARAKTERYSTYKA I PROPONOWANE METODY WDROŻENIA W ISTNIEJĄCYCH SIECIACH IPv4 KORZYSTAJĄCYCH Z ROUTERÓW CISCO

**Streszczenie.** Artykuł stanowi wprowadzenie do protokołu IPv6 oraz jest przeglądem istniejących podejść dla zapewnienia współistnienia IPv6 i IPv4, na przykładzie homogenicznej infrastruktury sieciowej Cisco. W pierwszym rozdziale scharakteryzowano protokół IPv6 i porównano go z IPv4. Następnie opracowano koncepcje związane z adresowaniem IPv6. W głównej części opisano metody do zapewnienia koegzystencji dwóch protokołów IP. Scharakteryzowano podstawową opcję jaką jest podwójny stos, po dwa rodzaje tunelowania punkt-punkt i punkt-wielopunkt oraz w końcu translacje adresów NAT-PT.

**Słowa kluczowe:** sieci komputerowe, sieci IP, protokoly

## Introduction

Widespread use of computer networks and rapid growth of the Internet in recent years has caused the exhaustion of IPv4 addresses. Despite use of various techniques aimed at economical use of available pool, such as NAT, depletion of available addresses could not be avoided, but only moved in time. This situation has induced intensification of interests in IPv6 protocol. This protocol both increases available amount of addresses and also introduces several important changes in comparison to well-known IPv4 [1].

Migrating billions of computers and other network devices from IPv4 to IPv6 is not possible immediately. This process will take many years and knowing that, network equipment manufacturers have developed tools that allow coexistence of two versions of IP, both on the Internet and in local area networks. Cisco - one of the largest manufacturers of network devices - in IOS operating system, used by routers and switches, has implemented a number of interesting methods to ensure smooth functioning of both IPv4 and IPv6. These methods are: dual stack, point to point tunneling (manually configured tunnels and GRE tunnels), point to multipoint tunneling (6to4 tunnels or ISATAP tunnels) and NAT-PT mechanism [2].

In the article have been discussed important issues of transitioning from IPv4 to IPv6, which many companies will have to deal with. In the first part, the IPv6 protocol has been characterized and compared to the IPv4. Also, concepts connected with IPv6 addressing have been described. In the second part it has been discussed methods to provide the coexistence of the two IP protocols. It has been characterized the primary option which is the dual stack, two types of both point to point and multipoint tunnels and finally - address translation NAT-PT.

## 1. IPv6 protocol

### 1.1. Differences between IPv6 and IPv4

An IPv4 address is 32 bits long and is represented by decimal characters. An IPv6 address is 128-bit binary value and can be written as 32 hexadecimal characters. Apart from this fundamental difference connected with providing a sufficiently large number of available addresses, IPv6 introduces many improvements and enhancements in comparison to its precursor. The most important are: addressing reformation, simplification of the header being added in an encapsulation process, improved security issues and a wide range of migration strategies [1].

Table 1. IPv4 and IPv6 – a short comparison

	IPv4	IPv6
Address size	32 bits	128 bits
Address example	192.168.10.101	2001:db8a::3257:9652
Number of address	4.294.467.295	3.4*10 <sup>38</sup>
Header size	20 octets	40 octets
QoS	Type of service field	Flow label field
Control messages	ICMP	ICMPv6
Checksums	Present	Moved to data link layer
Address configuration	Manual or DHCPv4	Manual, DHCPv6 or auto-configuration

Reformed addressing means no broadcast messages, ability to have multiple IPv6 addresses on a single physical link, which increases the reliability of connections and also auto-configuration with use of data link layer address. The simplification of the header has been realized by reducing number of fields to 8 and simultaneous increasing of its size to 40 octets (see Fig. 1). Smaller number of fields and no need for processing checksums allows to increase efficiency of routing [2].

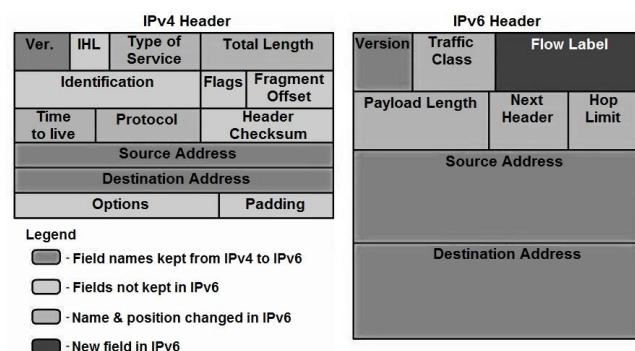


Fig. 1. IPv4 and IPv6 headers [2]

### 1.2. IPv6 addressing concepts

As mentioned before, an IPv6 address is 128-bit binary value, being written as eight groups of 16-bit values separated by colons. IPv4 addresses had fixed notation. The IPv6 addresses does not require a complete disclosure. It can be shortened according to certain rules. An example of IPv6 address and the way of shortening it is shown in Fig. 2 [2].

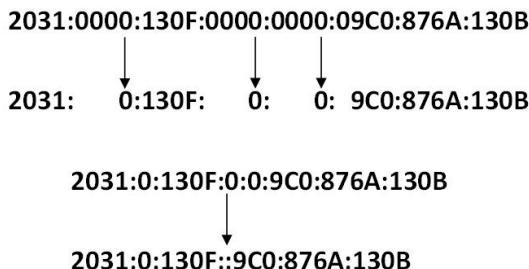


Fig. 2. Method of IPv6 address shortening [2]. In the first phase leading zeros have been removed. In the second phase, neighboring fields made up of zeros have been replaced by two colons

In general, there are two rules. First, says that the leading zeros in a field does not require to be written (e.g. field 0000 can be written as 0 or 08B1 can be written as 8B1). The second - successive fields composed of zeroes can be replaced by two colons (this method can be used only once). The rules allows to significantly reduce the size of most addresses [2].

IPv6 addresses can be divided into several major groups:

- global unicast addresses (see Fig. 3), which are equivalent to IPv4 public addresses. Each address consists of 48-bit global routing prefix and 16-bit subnet field. Last 64 bit is an interface identifier (identifies a host). These addresses start from 2000::/3.
- private addresses, which are not transferred outside the local network (e.g. local-link addresses (see Fig. 4), start with FE8, FEA or FEB)
- loopback address - 0:0:0:0:0:0:1 (::1), designed for tests, equivalent to 127.x.x.x IPv4 addresses group.
- unspecified address - 0:0:0:0:0:0:0 (::), used when sending device does not know its own address
- group addresses – start from FF::/8, used for example by routing protocols like RIP or EIGRP
- special reserved addresses - e.g. group of addresses for described 6to4 tunneling

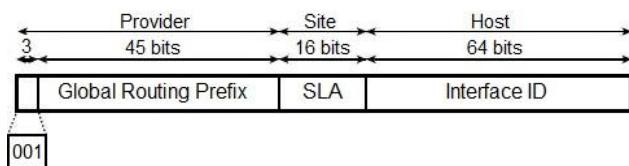


Fig. 3. Global unicast address scheme [5]

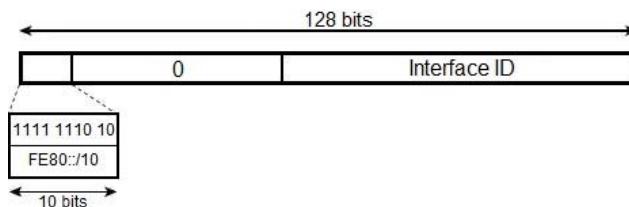


Fig. 4. Local-link address scheme [4]

## 2. Methods to ensure the coexistence of IPv4 and IPv6 protocols

Move from lack of IPv6 support to full support of this protocol does not occur instantaneously. In large companies, this process starts with moving to IPv6 only several routers, servers and hosts. Over time, number of devices switched to the new protocol in the organization begins to grow and at some point, IPv6 will completely replace IPv4 and support of this protocol will be disabled. Process of this gradual transition will last many years. The smooth transition to IPv6 is possible by three groups of tools [3]:

- Dual stack
- Tunneling
- NAT-PT

### 2.1. Dual stack

Primary and most commonly used method for the coexistence of IPv6 and IPv4 in a network is the dual stack (see Fig. 5). It consists in configuration of IPv6 routing protocols and IPv6 addresses on all routers and hosts in a network, that have to forward IPv6 packets. A dual-stack device chooses which stack to use based on the destination address of the packet. If IPv6 is available, then a dual-stack host should prefer it for communication. IPv4-only applications continue to work as before. New and modified applications can use both IP layers [2].

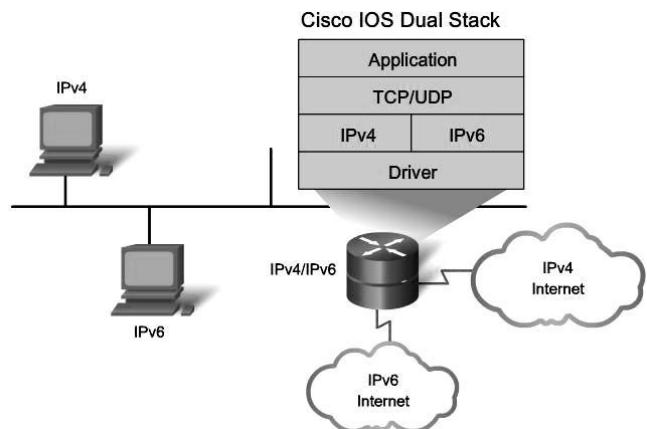


Fig. 5. Basic concept of the Dual Stack [2]

In the future the aim should be to ensure full coexistence of both versions of the IP protocol and then building new networks based only on IPv6, however this will be a long term process. At the present in many large networks there is a need to allow IPv6 communication for only a specific group of hosts or due to size of a network, simultaneous enabling IPv6 support is a problem. For such cases have been developed methods based on encapsulation of an IPv6 packet in an IPv4 packet [3].

### 2.2. Point to point tunnels

Tunneling is the process of encapsulation an IPv6 packet in an IPv4 packet by the router. The packet is treated by consecutive devices as a normal IPv4 unit and last router on the way de-encapsulates it and sends to its final destination. Tunneling does not require configuring IPv6 throughout the network, what allows to quickly provide IPv6 connectivity only in this part of the network, which needs it. The general concept of tunneling is shown in Fig. 6 [3].

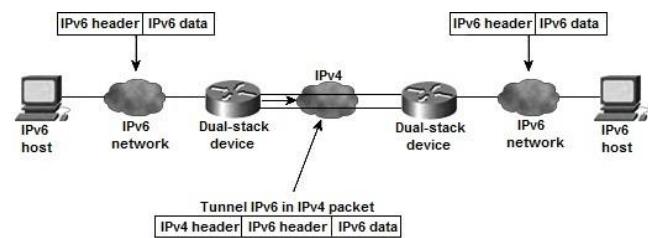


Fig. 6. General concept of tunneling [6]

A characteristic feature of point to point tunnels is that only one device can be located at each side of a tunnel. For each pair of IPv6 hosts, which have to communicate with each other, it is necessary to create a separate tunnel. Routers on the end of a tunnel treat the tunnel interfaces as serial point to point links [3].

The two available types of point to point tunnels are MCT (Manually Configured Tunnels) and GRE tunnels (Generic Routing Encapsulation). These tunnels connects many similarities: both use virtual point to point link to transmit packets, in both

cases it is possible to configure IPv6 IGP routing protocols on these virtual links and finally in both methods it is necessary to set up the source and destination IPv4 addresses of the tunnel statically. The difference is greater flexibility of GRE tunnel, which can be understood as the ability to send many passenger protocols and the use of transport protocols (encapsulating passenger protocols) other than IPv4. Sending passenger protocols is possible due to additional header placed between IPv6 and IPv4 headers [2, 3].

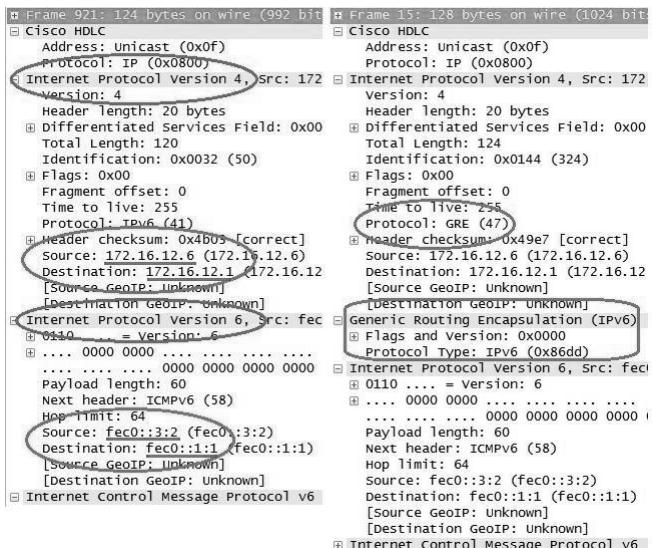


Fig. 7. Comparison of frames outgoing from router with tunneling enabled. MCT on the left, GRE on the right side; In both cases an IPv6 packet is encapsulated in an IPv4 packet. The source and destination IPv4 addresses, added to the IPv4 headers, are known from configuration of the tunnels. The only difference – GRE has an additional header between the IPv4 and the IPv6 header

Basic configuration of point to point tunnels is relatively simple. It consists in selection of IPv4 addresses, that will be used as the source addresses for the two routers, between which an IPv6 connectivity has to be established. Next step is to create tunnel interfaces on both routers and assign them source and destination IPv4 addresses. Finally, according to the needs, to select the mode of the tunnel (MCT or GRE) and to assign IPv6 addresses to external router interfaces between which an IPv6 link has to be provided [3, 4].

### 2.3. Point to multipoint tunnels

When IPv6 traffic is occasional and its size is difficult to predict, point to multipoint tunnels can be a good solution. These tunnels allow a single router to send packets to multiple routers with use of a single tunnel interface. The encapsulation process is similar to previously mentioned point to point tunnels. The main difference is the addition of an essential information, which allows a sending router to direct packets to an appropriate destination. The destination IPv4 address of the tunnel is embedded in the destination IPv6 address of the packet. To allow this concept to work, an appropriate addressing plan is required, which in turn depends on the selected multipoint tunnel type [3].

In the multipoint topology, under certain conditions, new devices can be connected to the tunnel without performing additional configuration on existing routers, what can be considered as an advantage. Moreover, this type of tunnels, in contrast to point to point tunnels, do not support IGP IPv6 routing protocols and thus require the use of static routes or BGP. Their use is also associated with a dynamic transmission of each packet, which in turn uses relatively a lot of router resources. Furthermore, multipoint tunnels configuration method are slightly more complicated in comparison to the previously described methods [3].

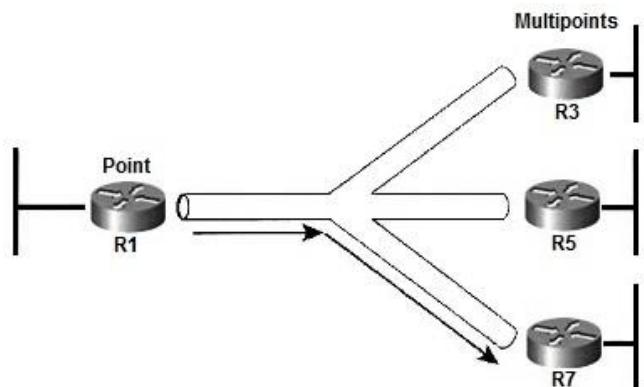


Fig. 8. Concept of point to multipoint tunneling [3]

There are two main methods of multipoint tunneling: automatic 6to4 tunnels and ISATAP tunnels. To use the 6to4 tunnel it is necessary to decide while planning, whether global unicast IPv6 addresses or special reserved block of IPv6 addresses starting from 2002::/16 are applied. If all traffic from the Internet to the organization uses IPv4 only, then the use of the reserved address range is recommended. It simplifies the configuration process and allows to exploit advantage of the multipoint tunnels, which is the ability to add new hosts without reconfiguring existing routers. On the other hand, if the company needs to apply IPv6 addresses for Internet connections, the use of global unicast addresses is indispensable. The important thing is how router determines to which endpoint of the tunnel to send the packet. In case of using the reserved block of IPv6 addresses, the source and destination addresses of the tunnel are stored in second and third quartet of the source and destination IPv6 addresses, converted to hexadecimal values. For example, the packet sent from the host with IPv6 address 2002:AC10:C06:3::1/64 to IPv6 2002:AC10: C01::1/64, when reaches the tunneling router, receives an IPv4 header with 172.16.12.6/30 source address, and will be directed to 172.16.12.1/30 destination address. These addresses have been determined by converting AC10:C06 and AC10:C01 form hexadecimal to decimal representation. In this way, the proper router can receive a packet and, after removing of IPv4 header, send it to the target IPv6 host. The situation is different when using global unicast addresses. Encoding the source and destination IPv4 addresses in IPv6 addresses is not possible because IPv6 addresses are allocated to the company by the external organization. This problem is solved by recursive route search by the router forwarding packets through its tunnel interface. In practice, it means the need to define specific static routes for the tunnel interface and this in turn brings more work when topology is changed [3, 4].

The second method of multipoint tunneling is ISATAP (Intra-site Automatic Tunnel Addressing Protocol). This concept, in some points, is similar to previously described 6to4. The tunnel interfaces use IPv6 addresses, in which IPv4 addresses are embedded and there is a necessity to configure static routes to the endpoints. In contrast to 6to4, destination IPv4 address is placed in seventh and eight quartet of IPv6 address. Also, there is no possibility of using reserved block of addresses and all tunnel interfaces use IPv6 prefixes from the same subnet. In addition, these tunnels can build interface identifier on the basis of network card MAC address (modified EUI-64). The tunneling router determines destination of the IPv6 packet by searching routes, previously added to its routing table. After receiving the packet, router checks the next hop IPv6 address for a matching route, and knowing that ISATAP is the used tunnel mode, it looks for destination IPv4 address in the last two quartets of found next hop address. This IPv4 address will be inserted into an additional header and the packet will be treated as an usual IPv4 packet by all routers on the way to the destination [3].

Frame 9: 124 bytes on wire (992 bits), 124 bytes captured (992 bits) on interface Cisco HDLC	
Internet Protocol version 4, Src: 172.16.12.6	Version: 4
Header length: 20 bytes	Header length: 20 bytes
Differentiated Services Field: 0x00 (DSCP 0)	Differentiated Services Field: 0x00 (DSCP 0)
Total Length: 120	Total Length: 120
Identification: 0x0010 (16)	Identification: 0x0014 (20)
Flags: 0x00	Flags: 0x00
Fragment offset: 0	Fragment offset: 0
Time to live: 255	Time to live: 255
Protocol: IPv6 (41)	Protocol: IPv6 (41)
Header checksum: 0xb25 [correct]	Header checksum: 0xb21 [correct]
Source: 172.16.12.6 (172.16.12.6)	Source: 172.16.12.6 (172.16.12.6)
Destination: 172.16.12.1 (172.16.12.1)	Destination: 172.16.12.1 (172.16.12.1)
[Source GeoIP: Unknown]	[Source GeoIP: Unknown]
[Destination GeoIP: Unknown]	[Destination GeoIP: Unknown]
Internet Protocol Version 6, Src: 2002:ac10:c06::1	Internet Protocol Version 6, Src: 2002:ac10:c06::1
0110 .... = Version: 6	0110 .... = Version: 6
.... 0000 0000 .... .... .... = Tr	.... 0000 0000 .... .... .... = Tr
..... 0000 0000 0000 0000 0000 = Fl	..... 0000 0000 0000 0000 0000 = Fl
Payload length: 60	Payload length: 60
Next header: ICMPv6 (58)	Next header: ICMPv6 (58)
Hop limit: 64	Hop limit: 64
Source: 2002:ac10:c06::1:1	Source: 2000:0:1::9:0:5ef0:ac10:c06
[Source 6to4 Gateway IPv4: 172.16.12.6]	[Source ISATAP IPv4: 172.16.12.6]
[Source 6to4 SLA ID: 1]	[Destination: 2000:0:1::1:1]
Destination: 2002:ac10:c01::1	[Source GeoIP: Unknown]
[Destination 6to4 IP4: 172.16.12.1]	[Destination GeoIP: Unknown]
[Destination 6to4 SLA ID: 0]	[Destination GeoIP: Unknown]
[Source GeoIP: Unknown]	[Destination GeoIP: Unknown]
[Destination GeoIP: Unknown]	[Destination GeoIP: Unknown]
Internet Control Message Protocol v6	Internet Control Message Protocol v6

Fig. 9. Comparison of frames outgoing from router with 6to4 (on the left) and ISATAP (on the right) configured; 6to4 IPv4 addresses are known from second and third quartets of IPv6 addresses. ISATAP source IPv4 address is determined from seventh and eighth quartets of IPv6 source address (destination IPv4 address is determined on the basis of next hop address of a matching static route)

## 2.4. NAT-PT

In some situations, at the stage of transition to IPv6, there is a need to ensure communication between hosts with different types of IP protocols support. For such cases has been developed a mechanism called NAT-PT (Network Address Translation-Protocol Translation). This method is similar to well known NAT, which has been helping to spare IPv4 addressing space, by translating private addresses to public for Internet connections. NAT-PT consists in translation source and destination addresses, along with whole headers, from IPv4 to IPv6 and vice versa [3].

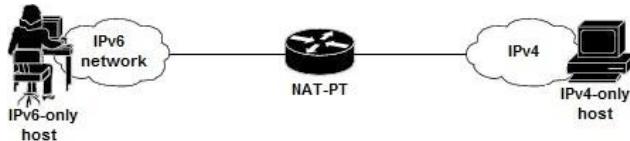


Fig. 10. Basic NAT-PT concept [7]

The configuration of NAT-PT is performed on the router by assigning to a given IPv4 address, an IPv6 address, to which it has to be converted when a packet is destined to an IPv6 host. Likewise for communication in the other direction (Fig. 11). For example, when the host with IPv6 address FEC0::3:2 tries to send a packet to an IPv4 host 10.1.3.2, it reaches first a router with IPv6, on which translation has been configured. Then the router converts the IPv4 header, simultaneously substituting the source and destination addresses with appropriate ones. The substituted source address is pre-configured on the router for translation purposes, destination address is IPv4 host address, in this case 10.1.3.2. It works analogously with the traffic sourced from the other direction [3].

R3#show ipv6 nat translations

Prot	IPv4 source	IPv6 source	IPv4 destination	IPv6 destination
---	IPv4 destination	IPv6 destination	IPv4 source	IPv6 source
---	10.1.3.2	FEC0::3:10	---	---
---	10.1.3.10	FEC0::3:2	---	---

Fig. 11. Show ipv6 nat translation command on Cisco router for configured NAT-PT; Source IPv4 address 10.1.3.2 is translated to FEC0::3:10. Source IPv6 address FEC0::3:2 is translated to 10.1.3.10

## 3. Summary

Complete disappearance of IPv4 protocol is not possible in the near future. Over the coming years it is expected that both IPv4 and IPv6 protocols will coexist in the networked world. Despite the variety of methods for ensuring the coexistence of IP protocols, the use of dual stack should be always considered at first. Even in case of initial rejection of this solution for tunneling, finally the dual stack must be the method to deploy and other methods should be exploited temporarily [3].

In case of choosing the concept of tunneling, advantages and disadvantages of available options should be considered to select proper way to meet the needs. The first thing to keep in mind is that every kind of tunneling consumes more router resources on which it is performed (in comparison to the dual stack). It is the result of additional encapsulation and de-encapsulation of packets. Point to point tunnels are good choice when regular and large traffic is expected on the tunnel interfaces. It is connected with no need to take dynamic decisions by the router to determine destination of the packets and therefore the router load is lower. In addition, configuration process of point to point tunnels is simple and does not require extensive knowledge. Point to multipoint tunnels are appropriate when expected IPv6 traffic is occasional or its size is difficult to predict. The tunneling router forwards the packets dynamically, based on various, depending on the tunnel type rules. The advantage of multipoint tunnels is the ability to add new hosts to the tunnel without performing any additional configuration on existing routers, but this require an appropriate addressing design and can be troublesome in certain situations [3].

The specific method is NAT-PT. It is applied when there's a need to provide connection between devices with different types of the IP protocol. One of the benefits of address translation is that no reconfiguring of existing hosts is required, because all the configurations are performed at the NAT-PT router. NAT-PT should not be used when other native communication technique is possible to apply [7].

The article does not exhaust the subject of the IP protocols and its coexistence. It constitutes only a sort of introduction and familiarization the Reader with IPv6 protocol and its implementation approaches on the example of Cisco networks. Wider descriptions and more detailed explanations of the described concepts can be found in Cisco technical documentations, which were also used while creating this article.

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# COMPARISON OF PERFORMANCE OF SYNCHRONIZATION ALGORITHMS FOR GRID CONNECTED POWER ELECTRONICS CONVERTERS ACCORDING TO PROPOSED EVALUATION QUALITY CRITERIA

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**Abstract.** In this paper a comparison of synchronization methods for power electronics converters is presented. Proposed evaluation criteria are based on Transmission System Operators requirements, as well as on criteria parameters based on requirements for design, computation and operation under normal/distorted conditions. Additionally a classification of various kinds of synchronization algorithms is discussed with a brief description of the role of power electronics in the modern power systems. All of the tested algorithms were subjected to appropriate tests validating the quality criteria for each of them. The tests were performed in terms of simulations. The investigation results are summarized in the table, which can serve as a basic selection guide.

**Keywords:** synchronization, smart grids, grid codes, phase locked loop (PLL), power electronics, renewable energy systems

## PORÓWNANIE DZIAŁANIA ALGORYTMÓW SYNCHRONIZACJI DLA ENERGOELEKTRONICZNYCH PRZEKSZTAŁNIKÓW PODŁĄCZONYCH DO SIECI WEDŁUG ZAPROPONOWANYCH KRYTERIÓW OCENY

**Streszczenie.** Niniejszy artykuł zajmuje się porównaniem metod synchronizacji z siecią dla energoelektronicznych przekształników. Zaproponowane kryteria oceny opierają się na wymaganiach Operatorów Systemów Przesyłowych, a także na wymaganiach związanych z projektowaniem samych algorytmów, mocą obliczeniową i działaniem w warunkach normalnych lub przy zakłóceniami występującymi w sieci. Przedstawiono również klasyfikację różnego rodzaju algorytmów służących do synchronizacji razem z ogólnym opisem roli energoelektronicznych układów we współczesnych systemach energetycznych. Wszystkie przedstawione algorymy zostały badane według odpowiednich testów, które pozwolily na ocenę kryteriów jakości dla każdego z nich. Badania zostały przeprowadzone w formie symulacji. Wszystkie wyniki są podsumowane w formie tabeli, która może służyć jako podstawowy przewodnik do doboru odpowiedniego algorytmu synchronizacji.

**Słowa kluczowe:** synchronizacja, sieci inteligentne, kody sieci, pętla synchronizacji fazowej (PLL), energoelektronika, odnawialne źródła energii

## Introduction

Modern industry is becoming more and more dependent on the correct operation of power converters. Power electronics is becoming one of the most important elements of today's reality. Many of converters applications are being considered as critical for plant production process. The power electronics technology allows the systems and the electric machines (motors and generators) to run efficiently and sustainably. Lack of this solution would make the electric motors run at full speed, and the renewable sources such as solar and wind power, wave energy, fuel cells could not be fed into the power grid. Modern, sustainable energy systems introduce the concept of "Smart grids", where the flow of the energy can be controlled in a sustainable way.

For grid connected power electronic converters basic information are frequency and angle of the utility network. For proper and safe operation phase angle of current or voltage of the fundamental component at the point of common coupling of a system or converter with the grid should be recognized "online" in a real time manner. If this condition is fulfilled the control of the flow of energy between the converter and the network can be achieved. Thus, the most efficient working mode of converters can be utilized.

It is worth noting that such performance mode of power electronics converters (maximum sync = ability to provide maximum efficiency) it is desirable from the point of view of the Transmission System Operators [7]. This due to the fact that having perfectly synchronized elements of the systems increases the stability margin of the system. Usually, various TSO's have different synchronization requirements. The set of such rules is stated in so-called grid codes. Grid codes are technical interconnection requirements for power networks.

Depending on the country, point of connection, grid condition, energy sources connected, load distribution, different requirements may occur. To show how the very definition of synchronization can be recognized, a quote from the polish TSO (PSE Operator) is presented: the synchronization is an "operation concerning the connection of the generating unit with the power system of connection of different power systems after their frequencies,

phase and voltages are equalized to reduce the disparity of the vectors of connected voltages to a value close to zero" [8].

## 1. Proposed evaluation criteria

The selection and evaluation of the effectiveness of the synchronization algorithm is difficult. The choice should be relevant to the TSO requirements and depend on application type. As described in [1], there are currently no criteria for the selection of synchronization algorithm for power converters. Another important issue is the possibility of comparing the performance of different synchronization algorithms. In the absence of such standards, the choice of the appropriate method is very limited. This shows that the need for a selection guide is straightforward. In order to create a reference guide for choosing a suitable synchronization algorithm define quality criteria are needed. A set of such evaluation criteria is presented on Figure 1.

The proposed solution is based on so called "three-legged stool model" [2], which is suitably modified according to the needs. The three legs are determined as follows: synchronization criteria leg, computation criteria leg and design criteria leg. The evaluation criteria determining the algorithm design phase consists of the following elements: application, noise immunity, single phase utilization, algorithms protection modes, required additional features (signal filtering etc.), methods of realization (analog, digital) and proposed in [1] THD level of a sinus of estimated phase angle.

Looking at the performance of the method, a very important aspect to take into account the computation criteria. This is due to the fact, that respectively established constraints can make our algorithm fast "enough" with cheaper solution. Criteria in this subgroup are determined by total number of signals and variables, number of addition/subtractions and multiplications/scaling operations, transient response, state variable/integrations, computational load and order of signals processed in a cascade.

But the most important part of those rules, basically the core, is the synchronization criteria set. The group consists of following criteria: phase angle jump overshoot level, phase angle settling time, phase frequency jump overshoot, phase frequency settling time, frequency adaptive operation, frequency estimation accuracy, method bandwidth and high frequency characteristics.

Quality criteria parameter			
Normal operation	Synchronization criteria	Computation criteria	Design criteria
	Bandwidth Frequency estimation accuracy (0-1) Frequency adaptive operation  High frequency characteristics  Phase-angle jump Settling time Phase-angle jump Overshoot  Phase frequency jump Settling time Phase frequency jump Overshoot	Computational load Order of signals processed in cascade State variables/integrations [36] Multiplications/scaling operations Additions/subtractions Total number of signals and variables Transient response	Noise immunity  Application Single phase utilization Protection modes Required additional features Method of realization  THD of sinus of phase angle (%) [4]
Operation under distortion			

Fig. 1. Proposed quality criteria

Going throughout the whole quality criteria selection set, one has to take into account two possible circumstances. Assessment of different synchronization algorithms should be carried out under normal conditions and during grid distortions.

## 2. Types of synchronization algorithms

In the literature there are many examples of different synchronization algorithms types. Number of methods used for synchronization is extremely high. Proper selection of the algorithm, taking into account the application, resistance to distortions, implantation method, usually is quite difficult. This was mainly due to the lack of proper classification of the synchronization methods. One of the first classifications of those algorithms is proposed in [1] and can be seen in Figure 2. It is based on the reference frame in which the algorithm is operating.

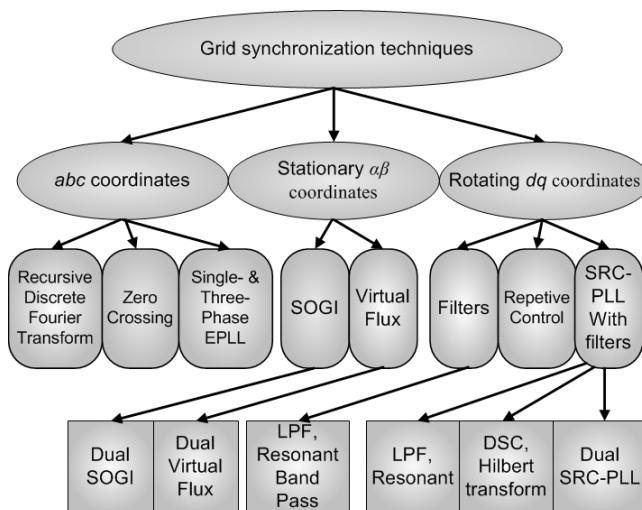


Fig. 2. Proposed classification method for synchronization algorithms [1]

Having in mind that power electronics converters cover a wide range of different kinds of applications and functions, a more detailed classification is proposed in [3], and the basic scheme of this classification can be seen in Figure 3.

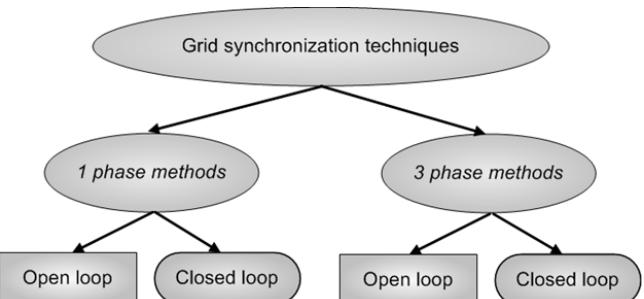


Fig. 3. The proposed general classification of synchronization algorithms [3]

For the purpose of the quality criteria evaluation several synchronization algorithms have been chosen. The following synchronization algorithms have been tested:

- Alpha beta filtering method [3];
- Simple Voltage Controlled Oscillator [3];
- Synchronous Reference Frame Phase Locked Loop (PLL-SRF) [4];
- Double Decoupled Synchronous Reference Frame PLL (DDSRF-PLL) [5, 6];
- Dual Second Order Generalized Integrators PLL (DSOGI-PLL) [5, 6];
- Dual Second Order Generalized Integrators with Quadrature Signals Generation and Positive Sequence Signals Cancelation (DSOGI-QSG-PSC) [4].

## 3. Methods evaluation

The selected methods are evaluated according to the proposed quality criteria. It has to be noted that only the operation in nominal (stable) conditions is considered. Only in the case of the frequency estimation accuracy and the THD calculation of a sinus of the estimated phase angle the evaluated synchronization algorithms were subjected to disturbed grid conditions. Figure 4 presents examined system structure. Simulated part is enveloped in gray rectangle. The other parts could be either sources of energy or loads, but for the grid-side converter (and synchronization algorithms) it does not matter.

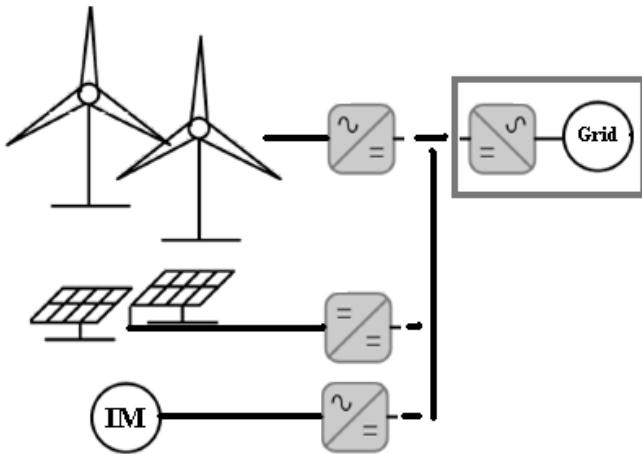


Fig. 4. Examined system structure

For determining the methods transient response algorithms start-up characteristics is taken into consideration. Figure 5 presents these characteristics for example selected algorithms.

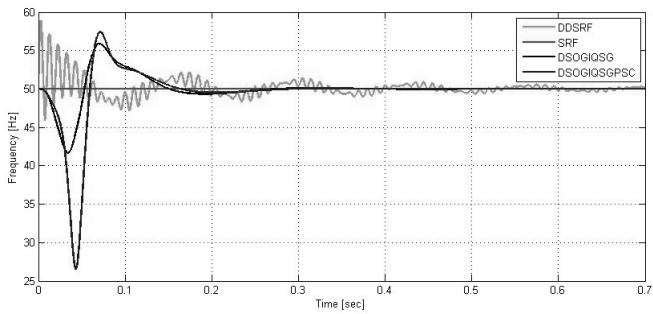


Fig. 5. Start-up of the selected synchronization methods

The fastest response is coming from SRF-PLL, which is achieving the settling time at 10 ms. The DDSRF-PLL has the settles at 350 ms and the DSOGIQSG-PLL, with the DSOGIQSG-PLL with the positive sequence cancellation have the settling time of 250 ms value. An example of the operation under distorted conditions during voltage disturbance for SRF-PLL can be seen in Figure 6.

It can be easily observed that during normal operation the algorithm can accurately determine the grid angle. However, in the case of grid voltage disturbance the estimation is not working well. As a result undulation in the angle signal appears.

It can be easily observed that during normal operation the algorithm can accurately determine the grid angle. However, in the case of grid voltage disturbance the estimation is not working well. As a result undulation in the angle signal appears.

Figure 7 presents the example algorithms operation during 15% THD grid distortion. The DDSRF-PLL, DSOGIQSG-PLL and the DSOGIQSGPSC-PLL synchronization algorithms settle down after 200 ms. The estimation error in their case is around  $\pm 1\%$ . This performance is acceptable. The SRF-PLL estimates the frequency with an error of  $\pm 10\%$ . The estimated signal is oscillating form 45 Hz to 50 Hz.

One of the proposed design criteria is the THD of sinus of an estimated phase angle. During normal operation all of the methods having the level of the THD below 1%. However, the appearance of any kinds of disturbances (for example harmonics), results in different performance for the algorithms. For testing the of the methods performance 15% THD distortion is applied to the grid voltage. Each of the methods achieves different result.

Namely the DSOGIQSGPSC-PLL is achieving 0.1% THD of the sinus of the estimated grid angle, the DSOGIQSG-PLL has 0.5%, the DDSRF-PLL has 0.2%, SRF-PLL hast the 1.5% THD level and the  $\alpha\beta$ -filtering method with SVCO have 15% THD level. Table 1 present the performance of the selected algorithm in terms of synchronization criteria.

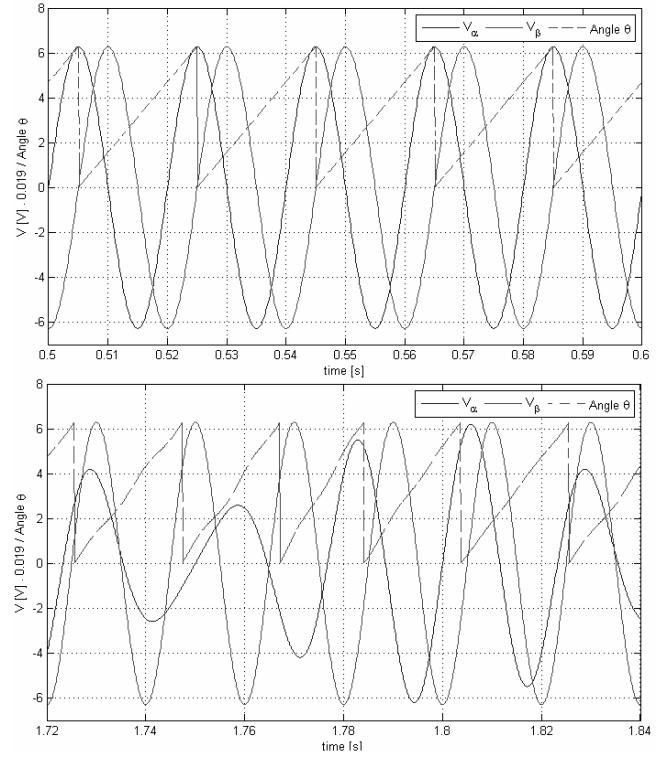


Fig. 6. The SRF-PLL method performance during voltage distortion

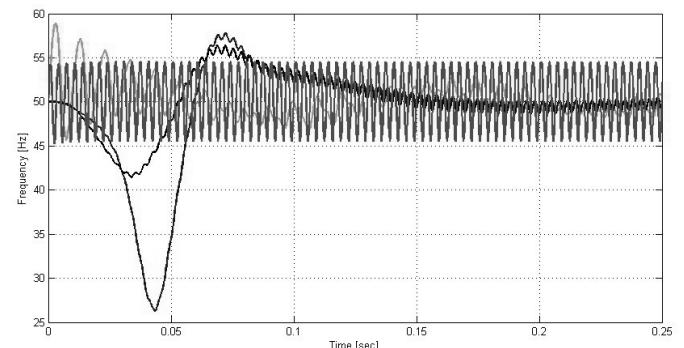


Fig. 7. Frequency estimation accuracy during grid operation with 15% THD

Table 2 presents the performance of the selected algorithms in terms of computation criteria. As it can be observed the more complex synchronization algorithm (order of signal processed, total number of mathematical operation – scaling, addition, multiplications) the better performance it can achieve. This also applies to the possibility of working under different disturbances, as it was presented before. On the other hand with the more complex synchronization structure higher computational load is needed, the transient response can be longer. But overall performance, the frequency estimation accuracy, frequency adaptive operation possibility are higher. But overall performance, the frequency estimation accuracy, frequency adaptive operation possibility are higher. But overall performance, the frequency estimation accuracy, frequency adaptive operation possibility are higher.

Table 1. The selected methods performance for the synchronization criteria

Synchronization criteria	Synchronization algorithm	Performance
Phase frequency jump overshoot	$\alpha\beta$ - filtering	15%
	SVCO	15%
	SRF-PLL	2%
	DDSRF-PLL	10%
	DSOIQSG-PLL	10%
	DSOIQSGPSC-PLL	8%
Phase frequency jump settling time	$\alpha\beta$ - filtering	150 ms
	SVCO	200 ms
	SRF-PLL	10 ms
	DDSRF-PLL	350 ms
	DSOIQSG-PLL	250 ms
	DSOIQSGPSC-PLL	250 ms
Phase angle jump overshoot	$\alpha\beta$ - filtering	15%
	SVCO	15%
	SRF-PLL	2%
	DDSRF-PLL	10%
	DSOIQSG-PLL	10%
	DSOIQSGPSC-PLL	8%
Phase angle jump settling time	$\alpha\beta$ - filtering	150 ms
	SVCO	200ms
	SRF-PLL	10 ms
	DDSRF-PLL	300 ms
	DSOIQSG-PLL	200 ms
	DSOIQSGPSC-PLL	200 ms
Frequency estimation accuracy	$\alpha\beta$ - filtering	0.4
	SVCO	0.4
	SRF-PLL	0.8
	DDSRF-PLL	0.9
	DSOIQSG-PLL	0.8
	DSOIQSGPSC-PLL	0.9
Frequency adaptive operation	$\alpha\beta$ - filtering	No
	SVCO	No
	SRF-PLL	Yes/No
	DDSRF-PLL	Yes
	DSOIQSG-PLL	Yes/No
	DSOIQSGPSC-PLL	Yes

## 4. Conclusions

This paper presents the evaluation of selected synchronization algorithms based on the proposed evaluation criteria. Choosing the appropriate synchronization method should be based on the determination of the application, power grid stiffness (with the emphasis on the power/voltage quality), possible ways of implementation. For helping in decision making, each of the selected methods were subjected to different types of tests. All of the results were collected in tablets, as well as presented in the article.

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Table 2. The selected methods performance for the computation criteria

Synchronization criteria	Synchronization algorithm	Performance
Transient response	$\alpha\beta$ - filtering	150 ms
	SVCO	200 ms
	SRF-PLL	10 ms
	DDSRF-PLL	350 ms
	DSOIQSG-PLL	250 ms
	DSOIQSGPSC-PLL	250 ms
Total number of signals and variables	$\alpha\beta$ - filtering	6
	SVCO	6
	SRF-PLL	10
	DDSRF-PLL	14
	DSOIQSG-PLL	16
	DSOIQSGPSC-PLL	18
Total number of additions and subtractions	$\alpha\beta$ - filtering	2
	SVCO	3
	SRF-PLL	3
	DDSRF-PLL	10
	DSOIQSG-PLL	7
	DSOIQSGPSC-PLL	9
Total number of multiplications and scaling	$\alpha\beta$ - filtering	4
	SVCO	4
	SRF-PLL	3
	DDSRF-PLL	11
	DSOIQSG-PLL	9
	DSOIQSGPSC-PLL	9
Order of signals processed	$\alpha\beta$ - filtering	2
	SVCO	1
	SRF-PLL	1
	DDSRF-PLL	1
	DSOIQSG-PLL	2
	DSOIQSGPSC-PLL	2
Computational load	$\alpha\beta$ - filtering	10%
	SVCO	10%
	SRF-PLL	40%
	DDSRF-PLL	60%
	DSOIQSG-PLL	50%
	DSOIQSGPSC-PLL	60%

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# MEASUREMENT OF THERMAL CONDUCTIVITY COEFFICIENT OF INSULATING LIQUIDS USING AUTHORING MEASUREMENT SYSTEM

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**Abstract.** The paper presents the results of measurements of the thermal conductivity coefficient of the selected insulating liquids according to the temperature. The value of the thermal coefficient of tested insulating liquids at temperatures from 20°C to 100°C was determined. Measurement of thermal conductivity was conducted by the use of presented authoring measurement system. The obtained results are essential to the design of power devices structures.

**Keywords:** thermal conductivity coefficient, insulating liquids, measurement techniques

## POMIAR WSPÓŁCZYNNIKA PRZEWODNOŚCI CIEPLNEJ WŁAŚCIWEJ CIECZY ELEKTROIZOLACYJNYCH Z WYKORZYSTANIEM AUTORSKIEGO UKŁADU POMIAROWEGO

**Streszczenie.** W artykule przedstawione zostały wyniki pomiarów współczynnika przewodności cieplnej właściwej wybranych cieczy elektroizolacyjnych w zależności od temperatury. Określona została wartość współczynnika przewodności cieplnej badanych cieczy elektroizolacyjnych w przedziale temperatury od 20°C do 100°C. Pomiar przewodności cieplnej przeprowadzono przy wykorzystaniu przedstawionego autorskiego układu pomiarowego. Uzyskane wyniki są istotne z punktu widzenia projektowania konstrukcji urządzeń elektroenergetycznych.

**Słowa kluczowe:** przewodność cieplna właściwa, ciecz elektroizolacyjne, technika pomiarowa

## Introduction

Power transformer is one of the most expensive and the most important power devices used for the transmission and distribution of electricity. For over a hundred years, for providing appropriate conditions of isolation and cooling, the power transformers are filled with mineral oils. Unfortunately, mineral oils are characterized by poor thermal properties, including a low thermal conductivity coefficient whereby, their cooling properties are not sufficient in many cases.

Several years ago there was the concept of using natural and synthetic esters in high voltage power transformers in place of heretofore applied mineral oils. The trend in the use of esters as insulating liquids results mainly from the increasingly restrictive regulations concerning environmental protection and the conditions of safe use of the power devices.

Natural and synthetic esters, unlike mineral oil, have a high coefficient of biodegradability and high flash point and burning, which makes them non-flammable liquids. Unfortunately, poor diagnosis of thermal properties of natural and synthetic esters is one of the main contraindications in their use. Currently, the use of natural and synthetic esters, due to their high price and poor identified properties, confined almost only to the distribution transformers installed in densely populated areas or particular fire hazard [3].

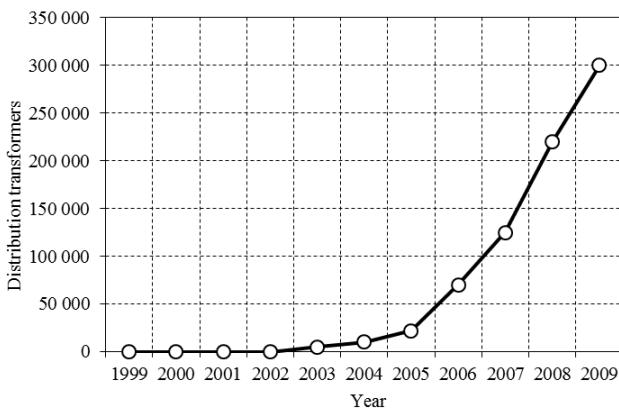


Fig. 1. Amount of distribution transformers in service filled with natural esters – worldwide [3]

Figure 1 shows the increase in the use of natural esters in distribution transformers installed worldwide. Since 2003, the diametrical growth in the number of distribution transformers

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filled with natural ester is recorded. Recently, a tendency to use of natural and synthetic esters in power transformers is also observed. However, their use has been limited mostly to situations that require a high level of fire protection and environment protection.

One of the key properties of thermal insulating liquids, which affect their ability to transport of heat, is the thermal conductivity coefficient. The thermal conductivity coefficient determines the amount of heat flowing through the cube with the edges of 1 m, within 1 s, and the temperature drop between the opposite faces of a cube equal to 1 K [6, 10].

Measurement of thermal conductivity of natural and synthetic esters is significant in terms of comparison of thermal conductivities of esters and previously used mineral transformer oils. For this purpose, system for measuring the thermal conductivity of the liquids was designed, constructed and tested. This article is dedicated to the measurements of the thermal conductivity coefficient  $\lambda$  using authoring measurement system.

## 1. Authoring measurement system

The chapter presents the authoring system for measuring thermal conductivity coefficient  $\lambda$  of insulating liquids. The concept of measuring the thermal conductivity coefficient using designed measurement system was also presented.

The measuring concept of thermal conductivity coefficient is to call in the sample of tested liquids thermal disturbances and to observe changes of the temperature distribution. In other words, the thermal conductivity coefficient  $\lambda$  is determined by passing through the sample of tested liquids specific heat flux and observing the changes of the temperature distribution on both sides at a fixed heat flow [7].

Figure 2 shows the authoring measurement system used to determine the thermal conductivity coefficient of liquids. Designed and built measurement system allows to call the thermal disorder  $\Delta T$ , and to measure it in the sample of tested liquids with the thickness  $d$  and the surface area  $S$ . Suitable thermal disturbance in the sample is obtained by using a heat source with power  $P$  and the use of the cooling system. On the basis of above mentioned values thermal conductivity coefficient of liquids is determined from the formula:

$$\lambda = \frac{P}{S} \cdot \frac{d}{\Delta T} \quad (1)$$

For measurement, a sample of the liquid should be placed between the main heater and cooler. It was assumed that the thickness  $d$  of the surface area  $S$  of all tested samples of liquid will be the same. The main heater with power  $P$  and surface area  $S$  is

designed to produce heat flux flowing through a sample of the liquid to the cooler. Heat flow generates temperature drop  $\Delta T$  in the sample liquid. The task of the cooler is to provide a constant temperature on the lower surface of the tested liquid. The measurement of temperature fall  $\Delta T$  and power readout of main heater occurs with a fixed heat flux. Knowing all of the physical quantities, using the formula (1) the thermal conductivity of the tested insulating liquids is defined. The correctness of the measurement is determined by the elimination of lateral heat loss and heat loss vertically upwards. Main heater should ensure the flow of heat perpendicularly down through the liquid sample. For this purpose, secondary heater which eliminates heat flow vertically upwards, or produces a heat flux, which causes the temperature values recorded directly above the main heater and the auxiliary heater are equal.

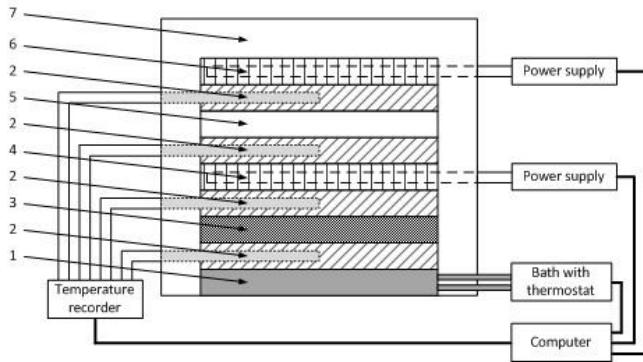


Fig. 2. Scheme of system to measure the thermal conductivity coefficient  $\lambda$  of liquids with associated measuring instruments and power supply, 1-cooler, 2-secondary electrode with probes (thermal), 3-sample of the liquids, 4-main heater, 5-secondary insulation, 6-secondary heater, 7-isolation [4]

The implementation of the measurement procedure also required the selection of a suitable temperature drop  $\Delta T$  on a sample of the liquid. The choice of temperature decrease was conditioned meeting two criteria. First, the drop in temperature should be as small as possible in order to accurately determine the effect of temperature on the measurement of the thermal conductivity coefficient  $\lambda$ . Secondly, this value should be large enough to reduce uncertainty of thermal conductivity measurement. On the basis of these criteria, it was decided that the temperature drop  $\Delta T$  in a sample of the liquid will be 5K.

## 2. Measurement system tests

This chapter describes the tests of authoring system for measuring thermal conductivity coefficient  $\lambda$  of the insulating liquids. Testing of the system was to check the tightness of the measuring system during the measurement, removing bubbling formed during filling of the system with liquid and measurement of the thermal conductivity of liquids with known from the literature thermal conductivity coefficient.

The first of the problems with which it was necessary to face during testing of the authorial measuring system were leaks that caused oil leakage from the system. Loss of liquid from the measuring system caused false results of measurements of thermal conductivity coefficient of tested liquid. As a result, the thermal conductivity obtained by the measurement of the thermal conductivity corresponded to the system air-insulating liquid. Leaks in the measurement system are eliminated through the use of additional sealing. Therefore, in the secondary electrodes located above and below the surface of the liquid sample used sealing in the form of rings. The use of additional sealing allowed to eliminate the problems of measuring leaks.

Another problem, which is of high importance for the accuracy of thermal conductivity coefficient  $\lambda$  of liquids, was air bubbles that were formed during the filling the system with tested liquid. In order to overcome this problem it was decided to enter into part of the system, that contains the examined liquid, (so called oil pan) two-channel tube with a diameter of 2 mm. One of

the channels is used for supplying liquid to the oil pan. Liquid is recessed into the system at a slight pressure. The second conduit is used to vent air and removal of air bubbles generated in the final stage of filling pan with insulating liquid. In addition, excess liquid associated with the increase in liquid volume during the measurements at high temperatures, is removed through this channel. This follows directly from the expansion of the tested insulating liquid coefficient.

Table. 1. Results of the authoring measurement system paired with the values given by literature

Kind of liquid	Thermal conductivity coefficient $\lambda$ [W/m·K]					
	Mineral oil Nynas Nytrö Taurus		Synthetic ester Midel 7131		Natural Ester Envirotemp FR3	
	From Literature <sup>13</sup>	From measurement	From Literature <sup>12</sup>	From measurement	From Literature <sup>11</sup>	
20°C	0.126	0.135	0.144	0.158	0.167	0.182
40°C	-	-	0.143	0.156	-	-
60°C	-	-	0.141	0.152	-	-
80°C	-	-	0.139	0.150	-	-
100°C	-	-	0.136	0.147	-	-

The authoring measurement system tests were carried out on the basis of thermal conductivity measurement of liquid with known from the literature values of the thermal conductivity coefficient  $\lambda$ . To the tests of the measurement system three insulating liquids were selected. For the tests mineral oil Nynas Nytrö Taurus, synthetic ester Midel 7131 and natural ester Envirotemp FR3 have been used. In the case of mineral oil and natural esters literature gives only the values of thermal conductivity at 20°C [2, 3, 9]. The correlation of the thermal conductivity coefficient and temperature is known only in the case of synthetic ester Midel 7131 [12]. Therefore, the measuring system tests were conducted using the listed insulating liquids at the temperature range in which the thermal conductivity of tested insulating liquids is known. It was assumed that the measurements of thermal conductivity coefficient is considered a successful, if the results do not differ by more than 10% of the data reported in the literature. The test results of authorial measuring system were summarized with the results given by the literature and they were presented in table 1.

Carried out tests of designed and constructed measurement system allow to state that obtained thermal conductivity values are within the accepted 10% margin of error. The same, the proper operation of the measuring system can be indicated.

## 3. Measurements' results

The chapter presents the results of measurements of the thermal conductivity coefficient  $\lambda$  of commonly used insulating liquids.

Effective heat dissipation from the transformer by the insulating liquid depends largely on convection and thermal conductivity [3]. Convection is associated with the thermal properties syndrome, such as viscosity, specific heat and thermal expansion coefficient. These properties lead to heat exchange with the environment by moving the liquid. Whereas, thermal conductivity is carried out in the liquid. All of these characteristics have a significant influence on the heat transfer coefficient  $\alpha$ , meaningful from the point of heat loss to the environment.

As mentioned in chapter 2, the literature data concerning the thermal conductivity coefficient of insulating liquids in most cases provide information regarding the temperature of 20°C. In contrast, the normal operating temperature of the transformer is in the range of 50-70°C. Therefore, it is necessary to determine the

value of the thermal conductivity coefficient of insulating liquids at a temperature, that is greater than 20°C. Literature data indicate that the thermal conductivity of mineral oils is about 0.11-0.16 W/m·K [2, 8], synthetic esters 0.15-0.16 W/m·K [1, 2, 8], and the natural esters 0.16-0.17 W/m·K [1, 2, 8, 9]. However, these thermal conductivity values refer to a temperature of 20°C.

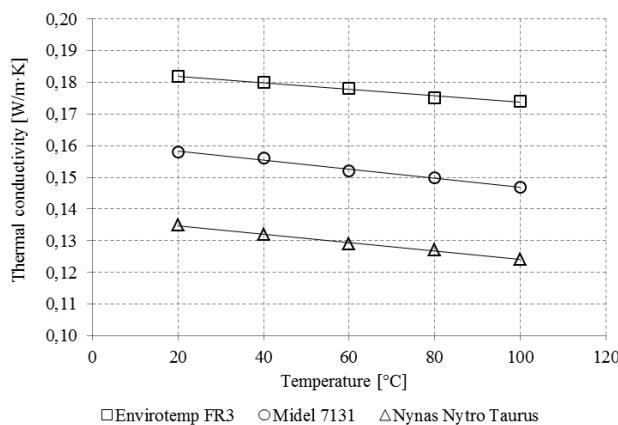


Fig. 3. Correlation graph of thermal conductivity coefficient and temperature for different types of insulating liquids

The graph 3 shows the correlation of the thermal conductivity coefficient of examined insulating liquids and the temperature determined by the use of the authoring measurement system. On the basis of the graph it can be concluded that the natural esters with respect to mineral oil and synthetic esters, have a much higher thermal conductivity coefficient in the entire temperature range. The thermal conductivity of the tested natural esters at temperature range from 20°C to 100°C is from 0.182 W/m·K to 0.174 W/m·K. In the case of other examined insulating liquids, the thermal conductivity is much lower, and in the analyzed temperature range is suitably from 0.158 W/m·K (for synthetic esters) to 0.147 W/m·K, and from 0.135 W/m·K to 0.124 W/m·K (for mineral oil). Thus, the high thermal conductivity coefficient is in favor of natural and synthetic esters. Thereupon, both natural and synthetic esters, compared to mineral oil, show a much higher viscosity, higher thermal conductivity coefficient  $\lambda$  can to some extent compensate higher viscosity of esters.

Thermal properties of insulating liquids are important for the design of power devices. Currently, no data are available concerning the impact of moisture and solid insulation aging products and insulating liquids on the thermal conductivity of the liquids. These results would avoid errors in calculations and mathematical simulations during the design phase of construction of power devices. In addition, weak identification of thermal properties, especially the thermal conductivity of new insulating liquids, like natural esters and synthetic esters is one of the concerns of their use as insulating liquids in high-voltage power transformers. Thus, there is a need to conduct research to determine the impact of various factors on the thermal properties of insulating liquids. These results will be used to specify which of the insulating liquids is characterized by the desired thermal properties.

#### 4. Summary

Built and designed measurement system can accurately determine the thermal conductivity coefficient  $\lambda$  of liquids. Due to the materials from which it has been made, as well as safety measure, it is possible to determine the thermal conductivity of the liquid in the temperature range from 20°C to about 100°C

Tests of designed and built measuring system was conducted on the insulating liquids with known from the literature data value of the thermal conductivity coefficient. On the basis of these tests, it can be concluded that the measurements' results obtained during the measurements of the authoring measurement system do not differ by more than 10% from the literature data.

On the basis of the obtained results, it can be concluded that the natural esters have the highest thermal conductivity coefficient within a temperature range from 20°C to 100°C. The thermal conductivity of the examined natural esters is more than 35% greater than the thermal conductivity of the tested mineral oil, and more than 15% greater than the thermal conductivity of the examined synthetic esters. In turn, the thermal conductivity of the tested natural esters is more than 17% greater than the thermal conductivity of the examined mineral oil. Moreover, presented results show correlation of thermal conductivity coefficient and temperature, which certainly facilitates designing and simulating the operation of power devices.

In order to clarify which of insulating liquids are characterized by greater ability to the heat transfer to ambient the measurements of thermal conductivity coefficient of insulating liquids should be supplemented with data concerning other properties that impact on the heat transfer coefficient  $\alpha$ . These studies should determine the impact of temperature, moisture and aging products of insulating liquid and solid insulation on each of analyzed thermal properties.

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# MODELLING OF TRANSIENT HEAT TRANSPORT IN CRYSTALLINE SOLIDS USING THE INTERVAL LATTICE BOLTZMANN METHOD (TWO-DIMENSIONAL MODEL)

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**Abstract.** In the paper the two-dimensional numerical modelling of heat transfer in crystalline solids is considered. In the mathematical description the relaxation time and the boundary conditions are given as interval numbers. The problem formulated has been solved by means of the interval lattice Boltzmann method using the rules of directed interval arithmetic.

**Keywords:** Boltzmann transport equation, interval lattice Boltzmann method, directed interval arithmetic

## MODELONANIE PRZEPŁYWU CIEPŁA W DWUWYMIAROWYM CIELE KRYSTALICZNYM ZA POMOCĄ INTERWAŁOWEJ METODY SIATEK BOLTZMANNA

**Streszczenie.** W artykule zaprezentowano dwuwymiarowy model numeryczny przepływu ciepła w ciele krystalicznym. W opisie matematycznym czas relaksacji i warunki brzegowe są zdefiniowane jako liczby przedziałowe. Sformułowane zagadnienie rozwiązyano za pomocą interwałowej metody siatek Boltzmana stosując skierowaną arytmetykę interwałową.

**Slowa kluczowe:** równanie transportu Boltzmana, interwałowa metoda siatek Boltzmana, skierowana arytmetyka interwałowa

## Introduction

In dielectric materials and also semiconductors the heat transport is mainly realized by quanta of lattice vibrations called phonons. Phonons always “move” from the part with the higher temperature to the part with the lower temperature. During this process phonons carry energy. This phenomena can be described by the Boltzmann transport equation transformed in the phonon energy density [4].

Such approach in which the parameters appearing in the problem analyzed are treated as constant values is widely used. Here, in the mathematical model describing the heat transfer in a thin silicon film the interval values of relaxation time and boundary conditions have been assumed.

The problem analyzed has been solved using an interval version of the lattice Boltzmann method using the rules of directed interval arithmetic.

## 1. Directed interval arithmetic

Let us consider a directed interval  $\bar{a}$  which can be defined as a set  $\mathbf{D}$  of all directed pairs of real numbers defined as [3, 6]

$$\bar{a} = [a^-, a^+] := \{\bar{a} \in \mathbf{D} \mid a^- \in \mathbf{R}, a^+ \in \mathbf{R}\} \quad (1)$$

where  $a^-$  and  $a^+$  denote the beginning and the end of the interval, respectively.

The left or the right endpoint of the interval  $\bar{a}$  can be denoted as  $a^s$ ,  $s \in \{+, -\}$ , where  $s$  is a binary variable. This variable can be expressed as a product of two binary variables and is defined as follows

$$\begin{aligned} + &= - - = + \\ + &- - + = - \end{aligned} \quad (2)$$

An interval is called proper if  $a^- \leq a^+$ , improper if  $a^- \geq a^+$  and degenerate if  $a^- = a^+$ . The set of all directed interval numbers can be written as  $\mathbf{D} = \mathbf{P} \cup \mathbf{I}$ , where  $\mathbf{P}$  denotes a set of all directed proper intervals and  $\mathbf{I}$  denotes a set of all improper intervals.

Additionally a subset  $\mathbf{Z} = \mathbf{Z}_p \cup \mathbf{Z}_i \in \mathbf{D}$  should be defined, where

$$\begin{aligned} \mathbf{Z}_p &= \{\bar{a} \in \mathbf{P} \mid a^- \leq 0 \leq a^+\} \\ \mathbf{Z}_i &= \{\bar{a} \in \mathbf{I} \mid a^+ \leq 0 \leq a^-\} \end{aligned} \quad (3)$$

For directed interval numbers two binary variables are defined. The first of them is the direction variable

$$\tau(\bar{a}) = \begin{cases} +, & \text{if } a^- \leq a^+ \\ -, & \text{if } a^- > a^+ \end{cases} \quad (4)$$

and the other is the sign variable

$$\sigma(\bar{a}) = \begin{cases} +, & \text{if } a^- > 0, a^+ > 0 \\ -, & \text{if } a^- < 0, a^+ < 0 \end{cases}, \quad \bar{a} \in \mathbf{D} \setminus \mathbf{Z} \quad (5)$$

For zero argument  $\sigma([0, 0]) = \sigma(0) = +$ , for all intervals including the zero element  $\bar{a} \in \mathbf{Z}$ ,  $\sigma(\bar{a})$  is not defined.

The sum of two directed intervals  $\bar{a} = [a^-, a^+]$  and  $\bar{b} = [b^-, b^+]$  can be written as

$$\bar{a} + \bar{b} = [a^- + b^-, a^+ + b^+], \quad \bar{a}, \bar{b} \in \mathbf{D} \quad (6)$$

The difference is of the form

$$\bar{a} - \bar{b} = [a^- - b^+, a^+ - b^-], \quad \bar{a}, \bar{b} \in \mathbf{D} \quad (7)$$

The product of the directed intervals is described by the formula

$$\bar{a} \cdot \bar{b} = \begin{cases} [a^{-\sigma(\bar{b})} \cdot b^{-\sigma(\bar{a})}, a^{\sigma(\bar{b})} \cdot b^{\sigma(\bar{a})}], & \bar{a}, \bar{b} \in \mathbf{D} \setminus \mathbf{Z} \\ [a^{\sigma(\bar{a})\tau(\bar{b})} \cdot b^{-\sigma(\bar{a})}, a^{\sigma(\bar{a})\tau(\bar{b})} \cdot b^{\sigma(\bar{a})}], & \bar{a} \in \mathbf{D} \setminus \mathbf{Z}, \bar{b} \in \mathbf{Z} \\ [a^{-\sigma(\bar{b})} \cdot b^{\sigma(\bar{b})\tau(\bar{a})}, a^{\sigma(\bar{b})} \cdot b^{\sigma(\bar{b})\tau(\bar{a})}], & \bar{a} \in \mathbf{Z}, \bar{b} \in \mathbf{D} \setminus \mathbf{Z} \\ [\min(a^- \cdot b^+, a^+ \cdot b^-), \max(a^- \cdot b^-, a^+ \cdot b^+)], & \bar{a}, \bar{b} \in \mathbf{Z}_p \\ [\max(a^- \cdot b^-, a^+ \cdot b^+), \min(a^- \cdot b^+, a^+ \cdot b^-)], & \bar{a}, \bar{b} \in \mathbf{Z}_i \\ 0, & (\bar{a} \in \mathbf{Z}_p, \bar{b} \in \mathbf{Z}_i) \cup (\bar{a} \in \mathbf{Z}_i, \bar{b} \in \mathbf{Z}_p) \end{cases} \quad (8)$$

The quotient of two directed intervals can be written using the formula

$$\bar{a} / \bar{b} = \begin{cases} [a^{-\sigma(\bar{b})} / b^{\sigma(\bar{a})}, a^{\sigma(\bar{b})} / b^{-\sigma(\bar{a})}], & \bar{a}, \bar{b} \in \mathbf{D} \setminus \mathbf{Z} \\ [a^{-\sigma(\bar{b})} / b^{-\sigma(\bar{b})\tau(\bar{a})}, a^{\sigma(\bar{b})} / b^{-\sigma(\bar{b})\tau(\bar{a})}], & \bar{a} \in \mathbf{Z}, \bar{b} \in \mathbf{D} \setminus \mathbf{Z} \end{cases} \quad (9)$$

In the directed interval arithmetic are defined two extra operators, inversion of summation

$$-_{\mathbf{D}} \bar{a} = [-a^-, -a^+], \quad \bar{a} \in \mathbf{D} \quad (10)$$

and inversion of multiplication

$$1/_{\mathbf{D}} \bar{a} = [1/a^-, 1/a^+], \quad \bar{a} \in \mathbf{D} \setminus \mathbf{Z} \quad (11)$$

So, two additional mathematical operations can be defined as follows

$$\bar{a} -_{\mathbf{D}} \bar{b} = [\bar{a}^- - \bar{b}^-, \bar{a}^+ - \bar{b}^+], \quad \bar{a}, \bar{b} \in \mathbf{D} \quad (12)$$

and

$$\bar{a} /_{\mathbf{D}} \bar{b} = \begin{cases} \left[ \frac{\bar{a}^{-\sigma(\bar{b})}}{b^{-\sigma(\bar{a})}}, \frac{a^{\sigma(\bar{b})}}{b^{\sigma(\bar{a})}} \right], & \bar{a}, \bar{b} \in \mathbf{D} \setminus \mathbf{Z} \\ \left[ \frac{\bar{a}^{-\sigma(\bar{b})}}{b^{\sigma(\bar{b})}}, \frac{a^{\sigma(\bar{b})}}{b^{\sigma(\bar{b})}} \right], & \bar{a} \in \mathbf{Z}, \bar{b} \in \mathbf{D} \setminus \mathbf{Z} \end{cases} \quad (13)$$

Now, it is possible to obtain the number zero by subtraction of two identical intervals  $\bar{a} -_{\mathbf{D}} \bar{a} = 0$  and the number one as the result of the division  $\bar{a} /_{\mathbf{D}} \bar{a} = 1$ , which was impossible when applying classical interval arithmetic [5].

## 2. Boltzmann transport equation

One of the fundamental equations of solid state physics is the Boltzmann transport equation (BTE) which takes the following form [1, 2]

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f = \frac{f^0 - f}{\tau_r} + g_{ef} \quad (14)$$

where  $f$  is the phonon distribution function,  $f^0$  is the equilibrium distribution function given by the Bose-Einstein statistic,  $\mathbf{v}$  is the phonon group velocity,  $\tau_r$  is the relaxation time and  $g_{ef}$  is the phonon generation rate due to electron-phonon scattering.

In order to take advantage of the simplifying assumption of the Debye model, the BTE can be transformed to an equation on carrier energy density of the form [1]

$$\frac{\partial e}{\partial t} + \mathbf{v} \cdot \nabla e = -\frac{e - e^0}{\tau_r} + q_v \quad (15)$$

where  $e$  is the phonon energy density,  $e^0$  is the equilibrium phonon energy density and  $q_v$  is the internal heat generation rate related to an unit of volume. The equation (15) must be supplemented by the boundary initial conditions.

Using the Debye model the relation between phonon energy density and lattice temperature is given by

$$e(T) = \left( \frac{9\eta k_b}{\Theta_D^3} \int_0^{\Theta_D/T} \frac{z^3}{\exp(z)-1} dz \right) T^4 \quad (16)$$

where  $\Theta_D$  is the Debye temperature of the solid,  $k_b$  is the Boltzmann constant,  $T$  is the lattice temperature while  $\eta$  is the number density of oscillators and can be calculated using the formula

$$\eta = \frac{1}{6\pi^2} \left( \frac{k_b \Theta_D}{\hbar \omega} \right)^3 \quad (17)$$

where  $\hbar$  is the Planck constant divided by  $2\pi$  and  $\omega$  is the phonon frequency.

## 3. Interval lattice Boltzmann method

The interval lattice Boltzmann method (ILBM) is a discrete representation of the Boltzmann transport equation. For two-dimensional problems the interval Boltzmann transport equation can be written as

$$\frac{\partial \bar{e}}{\partial t} + \mathbf{v} \cdot \nabla \bar{e} = -\frac{\bar{e} - \bar{e}^0}{\bar{\tau}_r} + q_v \quad (18)$$

where  $\bar{e}$  is the interval phonon energy density,  $\bar{e}^0$  is the interval equilibrium phonon energy density,  $\mathbf{v}$  is the phonon group velocity,  $q_v$  is the internal heat generation rate related to an unit of volume and  $\bar{\tau}_r = [\tau_r^-, \tau_r^+]$  is the interval relaxation time.

For two-dimensional model the discrete phonon velocities are expressed as [2]

$$\mathbf{c}_d = \begin{cases} (0, 0) & d = 0 \\ (\cos[(2d-1)\pi/2], \sin[(2d-1)\pi/2])c & d = 1, \dots, 4 \end{cases} \quad (19)$$

where  $c = \Delta x / \Delta t = \Delta y / \Delta t$  is the lattice speed,  $\Delta x$  and  $\Delta y$  are the lattice distances from site to site,  $\Delta t = t^{f+1} - t^f$  is the time step needed for a phonon to travel from one lattice site to the neighboring lattice site and  $d$  is the direction.

The interval lattice Boltzmann method algorithm has been used to solve the problem analyzed [1, 7].

The ILBM discretizes the space domain considered by defining lattice sites where the phonon energy density is calculated.

The lattice is a network of discrete points arranged in a regular mesh with phonons located in lattice sites. Phonons can travel only to neighboring lattice sites by ballistically traveling with the certain velocity and collide with other phonons residing at these sites according to Fig. 1 [1].

The discrete set of propagation velocities in the main lattice directions can be defined as (see eq. 19)

$$\begin{aligned} \mathbf{c}_0 &= (0, 0) & \mathbf{c}_1 &= (c, 0) & \mathbf{c}_2 &= (0, c) \\ \mathbf{c}_3 &= (-c, 0) & \mathbf{c}_4 &= (0, -c) \end{aligned} \quad (20)$$

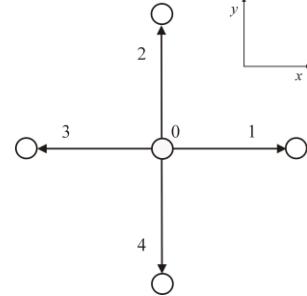


Fig. 1. Two dimensional 5-speed (D2Q5) lattice Boltzmann model

In the ILBM it is needed to solve five equations allowing to compute phonon energy in different lattice nodes according to the following equations

$$\begin{aligned} \frac{\partial \bar{e}_0}{\partial t} &= -\frac{\bar{e}_0 - \bar{e}_0^0}{[\tau_r^-, \tau_r^+]} + q_v \\ \frac{\partial \bar{e}_1}{\partial t} + c \frac{\partial \bar{e}_1}{\partial x} &= -\frac{\bar{e}_1 - \bar{e}_1^0}{[\tau_r^-, \tau_r^+]} + q_v \\ \frac{\partial \bar{e}_2}{\partial t} + c \frac{\partial \bar{e}_2}{\partial y} &= -\frac{\bar{e}_2 - \bar{e}_2^0}{[\tau_r^-, \tau_r^+]} + q_v \\ \frac{\partial \bar{e}_3}{\partial t} - c \frac{\partial \bar{e}_3}{\partial x} &= -\frac{\bar{e}_3 - \bar{e}_3^0}{[\tau_r^-, \tau_r^+]} + q_v \\ \frac{\partial \bar{e}_4}{\partial t} - c \frac{\partial \bar{e}_4}{\partial y} &= -\frac{\bar{e}_4 - \bar{e}_4^0}{[\tau_r^-, \tau_r^+]} + q_v \end{aligned} \quad (21)$$

The set of equations (21) must be supplemented by the boundary conditions

$$\begin{cases} x = 0, 0 \leq y \leq L: & \bar{e}(0, y, t) = \bar{e}(\bar{T}_{b1}) \\ x = L, 0 \leq y \leq L: & \bar{e}(L, y, t) = \bar{e}(\bar{T}_{b2}) \\ y = 0, 0 < x < L: & \bar{e}(x, 0, t) = \bar{e}(\bar{T}_{b3}) \\ y = L, 0 < x < L: & \bar{e}(x, L, t) = \bar{e}(\bar{T}_{b4}) \end{cases} \quad (22)$$

and the initial condition

$$t = 0: \quad \bar{e}(x, y, 0) = \bar{e}(T_0) \quad (23)$$

where  $\bar{T}_{b1} = [T_{b1}^-, T_{b1}^+]$ ,  $\bar{T}_{b2} = [T_{b2}^-, T_{b2}^+]$ ,  $\bar{T}_{b3} = [T_{b3}^-, T_{b3}^+]$  and  $\bar{T}_{b4} = [T_{b4}^-, T_{b4}^+]$  are the interval boundary temperatures,  $T_0$  is the initial temperature.

The approximation of the first derivatives using right-hand and left-hand sides differential quotients is as

$$\frac{\partial \bar{e}_i}{\partial t} = \frac{\bar{e}_i(x, y, t + \Delta t) - \bar{e}_i(x, y, t)}{\Delta t} \quad i = 0, 1, \dots, 4 \quad (24)$$

and

$$\begin{aligned} \frac{\partial \bar{e}_1}{\partial x} &= \frac{\bar{e}_1(x + \Delta x, y, t + \Delta t) - \bar{e}_1(x, y, t + \Delta t)}{\Delta x} \\ \frac{\partial \bar{e}_2}{\partial y} &= \frac{\bar{e}_2(x, y + \Delta y, t + \Delta t) - \bar{e}_2(x, y, t + \Delta t)}{\Delta y} \\ \frac{\partial \bar{e}_3}{\partial x} &= \frac{\bar{e}_3(x, y, t + \Delta t) - \bar{e}_3(x - \Delta x, y, t + \Delta t)}{\Delta x} \\ \frac{\partial \bar{e}_4}{\partial y} &= \frac{\bar{e}_4(x, y, t + \Delta t) - \bar{e}_4(x, y - \Delta y, t + \Delta t)}{\Delta y} \end{aligned} \quad (25)$$

Thus one obtains the approximate form of the interval Boltzmann transport equations for 2D problem in five directions of the lattice [1, 2]

$$\begin{cases} (\bar{e}_0)^{f+1}_{i,j} = (1 - \Delta t / \bar{\tau}_r)(\bar{e}_0)^f_{i,j} + \Delta t / \bar{\tau}_r \cdot (\bar{e}_0^0)^f_{i,j} + \Delta t q_v \\ (\bar{e}_1)^{f+1}_{i+1,j} = (1 - \Delta t / \bar{\tau}_r)(\bar{e}_1)^f_{i,j} + \Delta t / \bar{\tau}_r \cdot (\bar{e}_1^0)^f_{i,j} + \Delta t q_v \\ (\bar{e}_2)^{f+1}_{i,j+1} = (1 - \Delta t / \bar{\tau}_r)(\bar{e}_2)^f_{i,j} + \Delta t / \bar{\tau}_r \cdot (\bar{e}_2^0)^f_{i,j} + \Delta t q_v \\ (\bar{e}_3)^{f+1}_{i-1,j} = (1 - \Delta t / \bar{\tau}_r)(\bar{e}_3)^f_{i,j} + \Delta t / \bar{\tau}_r \cdot (\bar{e}_3^0)^f_{i,j} + \Delta t q_v \\ (\bar{e}_4)^{f+1}_{i,j-1} = (1 - \Delta t / \bar{\tau}_r)(\bar{e}_4)^f_{i,j} + \Delta t / \bar{\tau}_r \cdot (\bar{e}_4^0)^f_{i,j} + \Delta t q_v \end{cases} \quad (26)$$

The total energy density is defined as the sum of discrete phonon energy densities in all the lattice directions

$$\bar{e} = \sum_{d=0}^4 \bar{e}_d \quad (27)$$

After subsequent computations the lattice temperature is determined using the formula

$$\bar{T}^{f+1} = \sqrt[4]{\bar{e}(\bar{T}^f) \Theta_D^3} \left/ \left( 9 \eta k_b \int_0^{\Theta_D / \bar{T}^f} \frac{z^3}{\exp(z) - 1} dz \right) \right. \quad (28)$$

#### 4. Results of computations

As a numerical example the heat transport in a silicon thin film of the dimensions  $200 \text{ nm} \times 200 \text{ nm}$  has been analyzed. The following input data have been introduced: the relaxation time  $\bar{\tau}_r = [6.36675, 6.69325] \text{ ps}$ , the Debye temperature  $\Theta_D = 640 \text{ K}$ , the boundary conditions  $\bar{T}_{b1} = [780, 820] \text{ K}$  and  $\bar{T}_{b2} = \bar{T}_{b3} = \bar{T}_{b4} = [292.5, 307.5] \text{ K}$ , the initial temperature  $T_0 = 300 \text{ K}$ . The lattice step  $\Delta x = \Delta y = 20 \text{ nm}$  and the time step  $\Delta t = 5 \text{ ps}$  have been assumed.

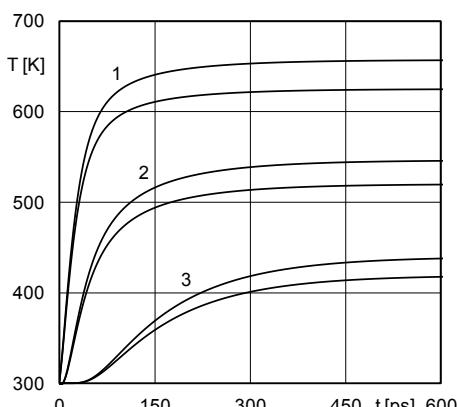


Fig. 2. The interval heating curves at internal nodes for  $q_v = 0$

Figure 2 presents the courses of the temperature function at the internal nodes  $(40, 20) - 1, (160, 40) - 2$  and  $(100, 100) - 3$  for the heat source  $q_v = 0$ . Figure 3 shows the courses of the temperature function at the same nodes like in Fig. 2 but for the heat source  $q_v = 10^{18} \text{ W/m}^3$ .

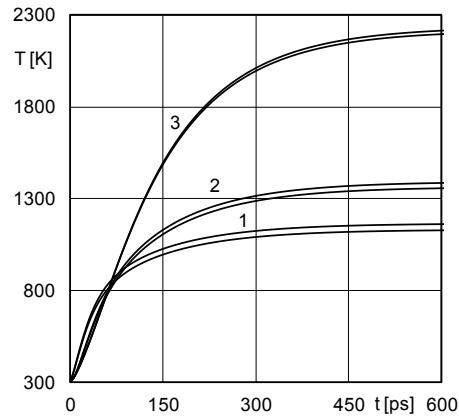


Fig. 3. The interval heating curves at internal nodes for  $q_v = 10^{18} \text{ W/m}^3$

#### 5. Conclusions

In the paper the Boltzmann transport equation with the interval values of the relaxation time and the boundary conditions has been considered. The interval version of the lattice Boltzmann method for solving 2D problems has been presented. The generalization of LBM allows one to find the numerical solution in the interval form and such an information may be important especially for the parameters which are estimated experimentally, for example the relaxation time.

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# PROTOTYP UKŁADU SCALONEGO Z DWUSTOPNIOWYM PRZETWARZANIEM IMPULSU DLA POTRZEB NISKOMOCOWEGO POMIARU CZASU WYSTĄPIENIA ZDARZENIA I AMPLITUDY ŁADUNKU WEJŚCIOWEGO

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**Streszczenie.** Artykuł prezentuje prototyp układu scalonego ASIC przeznaczonego do współpracy z krzemowymi detektorami o dużej pojemności. Mierzonymi wartościami są czas wystąpienia zdarzenia jak i ilość zdeponowanego ładunku. Celem zaprojektowanego układu jest obserwacja wpływu pojemności detektora (do kilkudziesięciu pF) na pracę i parametry dwustopniowego układu elektroniki front-end opartego koncepcyjnie o metodę przetwarzania typu Time-over-Threshold.

**Słowa kluczowe:** specjalizowane układy scalone, detektory półprzewodnikowe, wzmacniacz ładunkowy

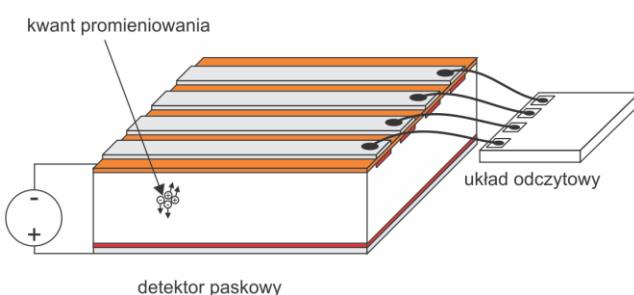
## LOW POWER PROTOTYPE OF THE INTEGRATED CIRCUIT WITH DUAL-STAGE PULSE PROCESSING FOR TIME AND AMPLITUDE MEASUREMENT

**Abstract.** This paper presents the prototype of the application specific integrated circuit designed for a silicon detector with large capacitance. The measured quantities are: the interaction time and the deposited charge. The aim of this project is to observe the influence of increasing sensor capacitance (up to tens of pF) on operation and performance of the dual-stage analog front-end electronics based on the concept of the Time-over-Threshold processing method.

**Keywords:** application specific integrated circuits, semiconductor detectors, charge-sensitive amplifiers

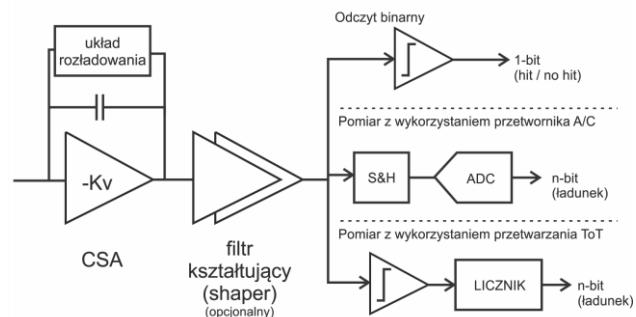
### Wstęp

Detektory paskowe znajdują zastosowanie przede wszystkim w detektorach śladowych dla Fizyki Wysokich Energii oraz w obrazowaniu z wykorzystaniem promieniowania X. Padający kwant promieniowania lub cząstka generuje w obszarze aktywnym detektora pary ładunków (elektron – dziura). Ponieważ detektor pracuje jako dioda spolaryzowana zaporowo, istniejące w detektorze pole elektryczne powoduje, że ładunki zbierane są na jego elektrodach. Ładunki te następnie wpływają do układu elektroniki odczytu (elektronika typu *front-end*) stwarzoszoną z detektorem (rys. 1). Zebrany ładunek jest poddawany dalszemu przetwarzaniu. Do najważniejszych parametrów tej klasy układów należą: pobór mocy, poziom szumów własnych wyrażanych jako ekwiwalentny ładunek szumowy ENC (*Equivalent Noise Charge*), szybkość i liniowość funkcji przetwarzania.



Rys. 1. System detekcyjny z detektorem paskowym

Jedną z metod przetwarzania impulsów w systemach detekcyjnych pracujących w trybie zliczania pojedynczych fotonów (*single-photon counting mode*) jest przetwarzanie typu *Time-over-Threshold* (rys. 2). Metoda ta, w przeciwieństwie do układu wykorzystującego typowy przetwornik analogowo-cyfrowy, pozwala na niskomocowy pomiar zdeponowanego w detektorze ładunku przy jednoczesnym zachowaniu często niewielkiego stopnia komplikacji układu [5]. Za pomocą komparatora i układu licznika mierzy się czas trwania impulsu napięciowego powyżej zadanego progu dyskryminacji. Długość ta niesie informację na temat ilości ładunku wejściowego.

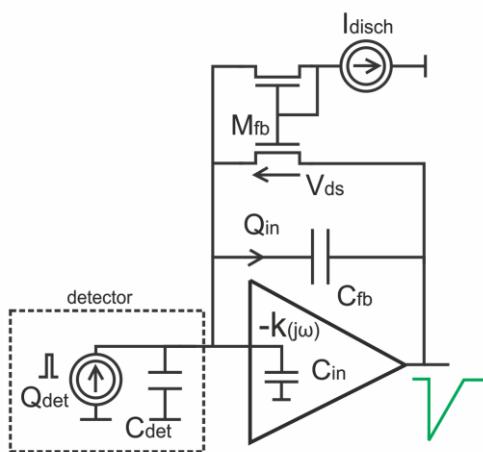


Rys. 2. Sposoby przetwarzania sygnałów z detektora pracującego w trybie zliczania pojedynczych fotonów

W zależności od typu przetwarzania analogowego poprzedzającego komparator, kształt charakterystyki przetwarzania (długość impulsu w funkcji ładunku wejściowego) może być różny. W realizacjach dla detektorów paskowych (pojemność sensora od kilku do kilkunastu pF) stosowane są filtry kształtujące (*shaper'y*). Charakterystyka taka jest często nielinowa, co ogranicza zakres dynamiczny i dokładność pomiaru ładunku, a także komplikuje interpretację cyfrowych danych wyjściowych. Istnieją jednak realizacje oferujące liniową charakterystykę przejściową. Są one oparte na rozładowaniu kondensatora  $C_{fb}$  w sprężeniu wzmacniacza ładunkowego za pomocą prądu stałego z wykorzystaniem np. lustra prądowego (rys. 3). Niestety, istniejące rozwiązania tego rodzaju można było znaleźć tylko dla detektorów o małej pojemności (detektory pikselowe).

Dotychczasowe badania autorów, poparte wykonanymi prototypami wskazują na to, iż uzyskanie liniowej funkcji przetwarzania przy pomiarze ładunku z detektorem o dużej pojemności (kilkadesiąt pF) przy zachowaniu bardzo niskiego poboru mocy spotyka się z szeregiem trudności i problemów [2, 3]. Należą do nich:

- znaczny spadek wzmacniania ładunkowego zwiększały się wraz ze wzrostem pojemności detektora  $C_{det}$ ,
- wypłaszczenie opadającego zbocza impulsu napięciowego na wyjściu wzmacniacza ładunkowego,
- redukcja stosunku sygnału do szumu SNR dla niskich progów dyskryminacji.



Rys. 3. Wzmacniacz ładunkowy z rozładowaniem prądem stałym

Najważniejszym problemem są sprzeczne wymagania odnośnie wartości pojemności  $C_{fb}$  w sprzężeniu zwrotnym wzmacniacza CSA. Aby zapewnić poprawną pracę układu należy zadbać o:

- wysoką ładunkowość (cały ładunek zdeponowany w detektorze jest zbierany w kondensatorze  $C_{fb}$ ),
- poprawną pracę  $M_{fb}$  jako lustra prądowego (w szczególności zapewnienie pracy w zakresie nasycenia).

Ladunek zebrany przez wzmacniacz CSA jest wyrażony poniższym równaniem:

$$Q_{fb} = \frac{C_{fb} \cdot (k_v + 1) \cdot Q_{in}}{C_{fb} \cdot (k_v + 1) + C_{in} + C_{det}} = Q_{in} \Bigg|_{C_{fb}(k_v + 1) \gg C_{in} + C_{det}} \quad (1)$$

gdzie:  $Q_{fb}$  – ładunek zebrany w pojemności sprzężenia zwrotnego  $C_{fb}$ ,  $C_{in}$  – pojemność tranzystora wejściowego,  $C_{det}$  – pojemność detektora,  $Q_{in}$  – ładunek zdeponowany w detektorze,  $k_v$  – wzmacnianie napięciowe rdzenia wzmacniacza CSA.

Zatem aby zebrać we wzmacniaczu ładunkowym cały wygenerowany ładunek efektywna pojemność wejściowa wzmacniacza ładunkowego  $C_{fb}(k_v + 1)$  musi być znacznie większa niż suma pojemności detektora  $C_{det}$  i pojemności tranzystora wejściowego  $C_{in}$ .

Wymagania dotyczące poboru mocy i zajmowanego obszaru krzemu determinują maksymalną osiągalną wartość wzmacnienia  $k_v$ . Dopasowanie szumowej wejściowej tranzystora wzmacniacza CSA do pojemności detektora wyznacza również pojemność tranzystora wejściowego  $C_{in}$  [1]. W związku z tym jedyny punkt swobody umożliwiający spełnienie powyższego wymagania stanowi pojemność sprzężenia zwrotnego  $C_{fb}$ .

Zapewnienie poprawnej pracy lustra prądowego w układzie sprzężenia zwrotnego wymaga przede wszystkim tego, aby tranzystor  $M_{fb}$  pracował w obszarze nasycenia. Niestety wymiary geometryczne tego tranzystora są ograniczone ze względu na konieczność minimalizacji wszelkich pasożytniczych pojemności wokół  $C_{fb}$ , co ma bezpośredni wpływ na minimalizację napięcia nasycenia  $V_{dssat}$  tranzystora  $M_{fb}$ . Możliwe jest jednak zapewnienie wyższego napięcia  $V$  w trakcie pracy poprzez zwiększenie wzmacnienia ładunkowego  $k_q$  wzmacniacza CSA. Wzmocnienie to jest odwrotnie proporcjonalne do pojemności  $C_{fb}$ . Aby zatem poprawić sytuację należy zmniejszać  $C_{fb}$ .

Powyższe rozważania prowadzą do sprzecznych wymagań w stosunku do  $C_{fb}$ . Niestety im większa pojemność detektora tym bardziej jest zagwarantowana zgodność wobec obu wymagań.

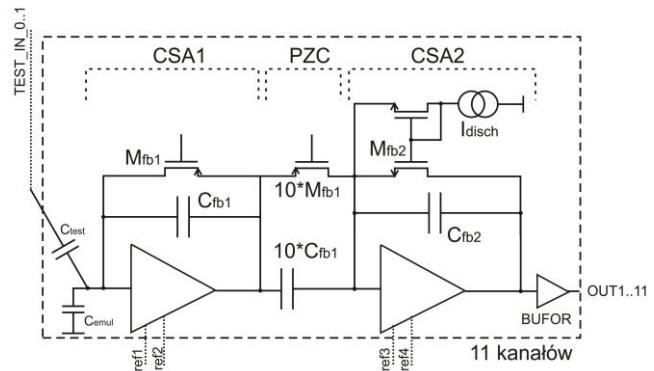
Jako możliwe rozwiązanie, autorzy zaproponowali koncepcję dwustopniowego przetwarzania ładunku wygenerowanego w detektorze [4]. W artykule przedstawiono projekt prototypowego specjalizowanego układu scalonego mającego za zadanie zweryfikować pracę przetwarzania dwustopniowego dla różnych pojemności detektora.

## 1. Architektura układu scalonego

Kanał elektroniki front-end składa się z dwóch stopni wzmacniaczy (rys. 2). Pierwszy stopień wzmacniacza ładunkowego CSA1 jest zoptymalizowany pod kątem wysokiej ładunkowości, a więc zapewnia wysoką efektywną pojemność wejściową (zdeterminowaną głównie przez wzmacnianie jądra wzmacniacza oraz pojemność sprzężenia zwrotnego  $C_{fb1}=150$  fF), oraz pod kątem niskich szumów. Stopień ten zużywa 1,59 mW mocy. Ładunek wejściowy jest całkowany przez pojemność  $C_{fb1}$ . Dzięki obecności obwodu PZC (Pole-Zero Compensation) sygnał jest przekazywany dalej w postaci wzmacnionego dziesięciokrotnie sygnału prądowego.

Tak wzmacniony sygnał prądowy jest powtórnie całkowany na kondensatorze  $C_{fb2}$  w układzie CSA2. Zastosowany w sprzężeniu zwrotnym układ ze źródłem prądowym rozładowuje kondensator prądem stałym. Dzięki temu, długość impulsu napięciowego na wyjściu wzmacniacza CSA2 jest proporcjonalna do ładunku wejściowego. Funkcjonalność ta pozwala na uzyskanie liniowej charakterystyki przejściowej nawet w warunkach nasycenia jądra wzmacniacza CSA2.

Zaprojektowany układ składa się z 11 kanałów odczytowych (rys. 4). Ładunek wejściowy wstrzykiwany jest przez kondensator  $C_{test} = 100$  fF. Wstrzykiwanie następuje dzięki wymuszeniu na okładce kondensatora skoku napięcia. Aby umożliwić testowanie przesłuchów między kanałami oraz uniknąć wyzwolenia wszystkich kanałów jednocześnie kondensatory  $C_{test}$  są sterowane z dwóch osobnych linii TEST\_IN\_0 i TEST\_IN\_1.



Rys. 4. Struktura układu scalonego

Zbadanie zachowania układów z wykorzystaniem detektorów paskowych o różnych pojemnościach wiązałoby się z zakupem wielu różnych, kosztownych sensorów. Dotychczasowe próby autorów dotyczące emulacji pojemności sensorów z wykorzystaniem zewnętrznych kondensatorów polegają na:

- dołączeniu zewnętrznego kondensatora ceramicznego w obudowie np. 0402 do wejścia układu scalonego poprzez wykonanie połączenia drutowego (wirebond) do specjalnie przygotowanego padu na obwodzie drukowanym,
- dołączeniu odpowiednio przyjętego (do zadanej pojemności) przy wykorzystaniu precyzyjnego miernika RLC przewodnika koncentrycznego i podłączeniu żyły sygnałowej do wejścia wzmacniacza ładunkowego a opłotu do masy.

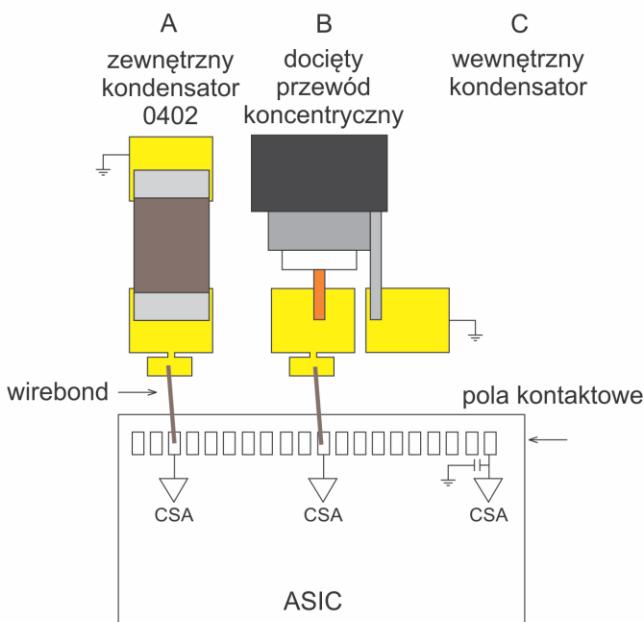
Niestety w takiej konfiguracji wpływ zewnętrznych zakłóceń docierających do układu utrudnia miarodajne pomiary (rys. 5). W związku z tym, w celu zbadania zachowania i zmian parametrów układu dla różnych pojemności detektora, każdy z kanałów ma na swoim wejściu podłączony kondensator zintegrowany w strukturze scalonej o różnej pojemności (od 0 pF do 32 pF).

Wyjście każdego z kanałów posiada bufor wyjściowy (NMOS: 200 μm × 180 nm,  $I_d = 200$  μA) przystosowany do sterowania obciążeniem do ok. 20 pF (np. pasywna sonda oscylkopowa) i jest dostępne na osobnym polu kontaktowym

OUT1..11. Dzięki temu, sygnał analogowy wprost po przetworzeniu będzie dostępny do dalszej analizy (nakładanie progu, zliczanie, pomiar czasu trwania, obserwacja efektu pełzania znacznika czasowego, analiza statystyczna itp.) z wykorzystaniem sprzętu laboratoryjnego.

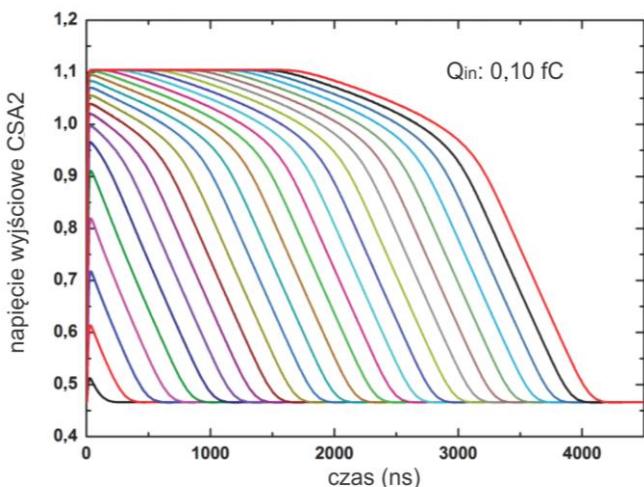
Na podstawie przeprowadzonych symulacji *post-layout* spodziewane parametry układu są następujące:

- poziom szumów: równoważny ładunek szumowy  $ENC = 892 \text{ e}^- \text{ rms}$  przy  $C_{det} = 30 \text{ pF}$ ,
- wzmacnianie ładunkowe  $240 \text{ mV/fC}$  (zachowuje liniowość do ok.  $2 \text{ fC}$  ładunku wejściowego),
- wzmacnianie czasowe  $400 \text{ ns/fC}$  (liniowość znacznie przekraczająca zakres  $10 \text{ fC}$ ),
- pobór mocy:  $2,05 \text{ mW/kanal}$ .



Rys. 5. Emulacja pojemności detektora za pomocą elementów zewnętrznych (A, B) oraz emulacja elementem wewnętrznym (C)

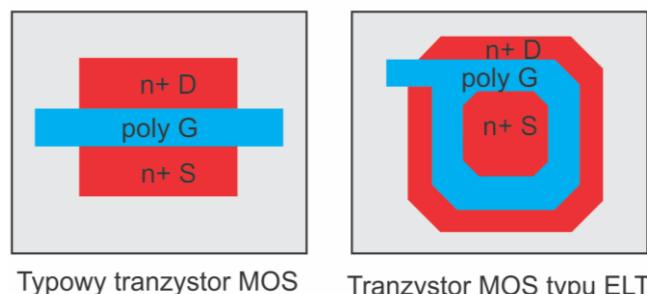
Na rysunku 6 przedstawiono napięciowe przebiegi wyjściowe wzmacniacza CSA2 dla różnych ładunków wejściowych (0–10 fC). Można zauważać, że pomimo nasycenia amplitudowego wzmacniacza występującego powyżej ok.  $2 \text{ fC}$  czas trwania impulsu jest nadal liniową funkcją ładunku wejściowego.



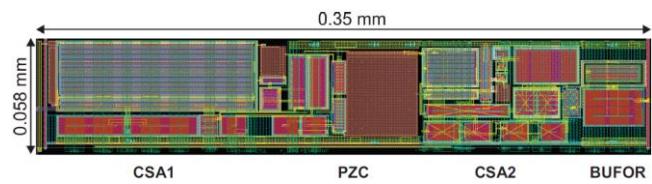
Rys. 6. Napięciowe przebiegi wyjściowe na wyjściu wzmacniacza CSA2 dla różnych ładunków wejściowych (0 – 10 fC)

## 2. Plan masek topologicznych

Plan masek kanałów pomiarowych został wykonany z myślą o aplikacji w docelowym, wielokanałowym układzie scalonym. Szerokość kanału jest zatem zgodna z odstępem między paskami detektora ( $58 \mu\text{m}$ ). Pojedynczy kanał zajmuje obszar  $58 \mu\text{m} \times 350 \mu\text{m}$ . Dzięki temu układ jest skalowalny, co zapewnia współpracę z detektorami o wielu paskach (np. 512). Aby poprawić odporność układu na efekty radiacyjne (przede wszystkim TID: *Total Ionizing Dose*) zastosowano tranzystory NMOS w topologii zamkniętej bramki ELT (*Enclosed Layout Transistor*) (Rys. 7). Warto dodać, że większość nowoczesnych technologii submikronowych ze względu na cienki tlenek bramkowy jest w dużej mierze stosunkowo odporna na niektóre z efektów radiacyjnych.



Rys. 7. Topologie tranzystorów MOS: typowego i w geometrii zamkniętej bramki

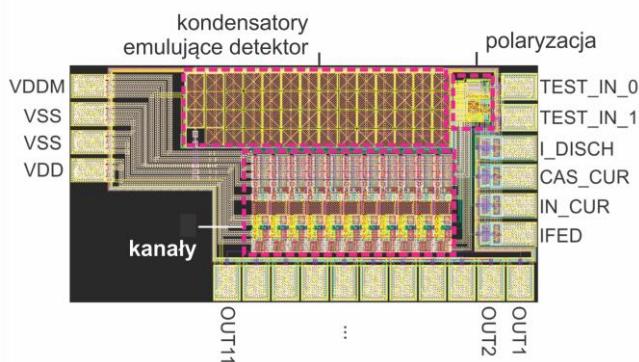


Rys. 8. Plan masek pojedynczego kanału układu scalonego

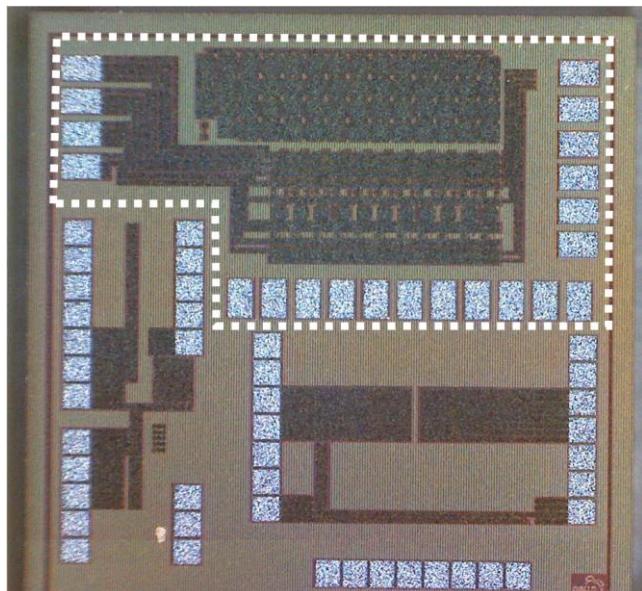
11 kondensatorów o wartościach pokrywających równomiernie zakres od 0 pF do 32 pF zostało zrealizowanych jako pojemności typu *mimcap* (kondensator pomiędzy warstwami metali 5 i 6 w technologii UMC 180 nm). W celu zmniejszenia rozrzutu parametrów tych elementów zbudowano matrycę składającą się z 55 identycznych kwadratowych struktur kondensatorów, a następnie odpowiednio połączono je między sobą i z wejściami poszczególnych kanałów odczytowych (rys. 8).

Plan masek zaprojektowanej struktury przedstawiono na rysunku 9. Zajmuje ona obszar  $1,49 \text{ mm} \times 0,76 \text{ mm}$ . Przy czym warto zaznaczyć, że zdecydowaną większość tego obszaru zajmują pola kontaktowe oraz pojemności emulujące różne pojemności detektora (które w docelowej aplikacji nie są potrzebne). Najistotniejszą część układu zajmuje mniej niż 20% powierzchni struktury. Należy zaznaczyć, że prototyp ten nie posiada padów wejściowych do podłączenia detektora – jego celem jest sprawdzenie wzmacniania (za pomocą wstrzykiwania ładunku z wykorzystaniem generatora zewnętrznego), poziomu szumów i liniowości charakterystyki dla różnych pojemności emulujących obecność detektora.

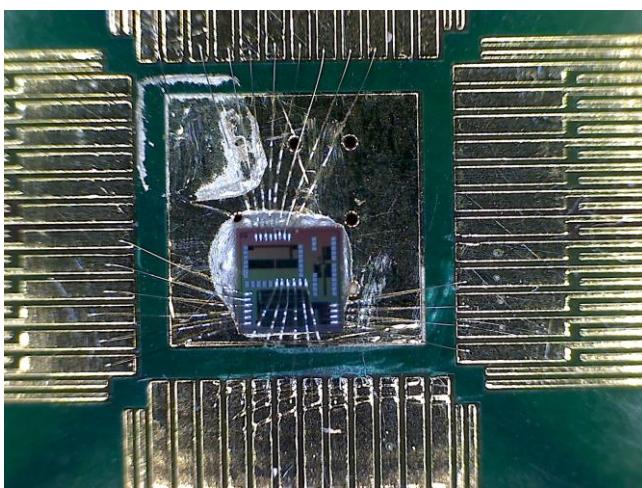
Prototypowy układ scalony został wyprodukowany maju 2013 r. w technologii UMC 180 nm CMOS, dzięki serwisowi EUROPRACTICE (Rys. 10). Przedstawiony układ prototypowy stanowi jeden z trzech niezależnych układów umieszczonych na jednej kości. Wykonany chip ma wymiary  $1,5 \text{ mm} \times 1,5 \text{ mm}$  na którym prezentowana struktura zajmuje ok. połowy powierzchni. Aby zminimalizować wpływ sąsiadujących struktur na wykonany układ otoczono go 4-rzędowym pierścieniem zabezpieczającym.



Rys. 9. Plan masek zaprojektowanej struktury: 1) obwody do polaryzacji, 2) kondensatory symulujące pojemność detektora, 3) kanały pomiarowe



Rys. 10. Fotografia wyprodukowanego układu scalonego



Rys. 11. Układ scalony umieszczony na stanowisku testowym

### 3. Podsumowanie

W wykonanym układzie zaimplementowano dwustopniowe przetwarzanie impulsu ładunkowego jako możliwe rozwiązanie problemu implementacji przetwarzania typu ToT z rozładowaniem prądem stałym dla detektorów o dużej pojemności w celu uzyskania charakterystyki przetwarzania o dużej liniowości. Rozwiązania zastosowane w prezentowanym układzie powinny umożliwić szybkie i kompletne sprawdzenie funkcjonowanie toru pomiarowego w szerokim spektrum pojemności sensora.

Do zalet przedstawionego układu można zaliczyć:

- bardzo niski pobór mocy (kilka mW),
- liniowa charakterystyka ToT dla dużych pojemności detektora,
- nieskomplikowana budowa.

Jako wady można wymienić (w porównaniu do przetwarzania przedstawionego na rys. 3):

- ograniczony zakres dynamiczny ale nadal bardzo duży,
- nieco większy pobór mocy (ok. 30%).

### Podziękowania

Praca powstała przy wsparciu Narodowego Centrum Nauki – nr: UMO-2011/02/N/ST7/01815.

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**Dr inż. Krzysztof Kasiński**  
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W roku 2012 uzyskał stopień doktora nauk technicznych w dyscyplinie Elektronika. Obecnie adiunkt w Katedrze Metrologii i Elektroniki wydziału Elektrotechniki, Automatyki, Informatyki i Inżynierii Biomedycznej Akademii Górnictwa-Hutniczej w Krakowie. Zainteresowania naukowe obejmują między innymi projektowanie specjalizowanych układów scalonych oraz systemów kontrolno-pomiarowych. Jest autorem lub współautorem ponad 30 prac naukowych.

**Mgr inż. Rafał Kleczek**  
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Ukończył Akademię Górnictwa-Hutniczą w 2009, kierunek: Elektronika i Telekomunikacja, specjalność: Mikroelektronika i aparatura biomedyczna. Obecnie jest na czwartym roku Studiów Doktoranckich na Wydziale IET, AGH. Pracuje jako asystent w Katedrze Metrologii i Elektroniki, AGH. Jego głównym zainteresowaniem naukowym jest projektowanie scalonych wielokanałowych układów elektroniki front-end do odczytu półprzewodnikowych detektorów promieniowania X.



## mgr inż. Tadeusz Ustaborowicz

### 79- lecie urodzin, 55 – lecie pracy zawodowej

Tadeusz Ustaborowicz urodził się 16 stycznia 1935 r. w Warszawie. Szkołę średnią „dużą maturę” z dyplomem technika elektryka ukończył w 1954 r. w technikum Zakładów Wytwórczych Przyrządów Pomiarowych („ERA”). Studia wyższe magisterskie (specjalność: miernictwo elektryczne) ukończył z wynikiem bardzo dobrym na Wydziale Elektrycznym Politechniki Warszawskiej w 1967r.

Ponad 55-letni okres pracy zawodowej JUBILATA można podzielić na dwa etapy:

- pierwszy (1951-1990) praca w przemyśle pomiarów i automatyki (w tym okresie od 1974 roku działalność wspomagająca czasopismo PAK – Pomiary Automatyka Kontrola);
- drugi (1990-2007) praca redakcyjna poświęcona całości PAK.

Pracę zawodową rozpoczął w 1951 r. w Zakładach „ERA” w Warszawie, pracując na różnych stanowiskach. Od stycznia 1969 r. rozpoczął pracę w Centrali Przemysłu Automatyki i Pomiarów (Zjednoczenie MERA w Warszawie). W latach 1969-1984 pełnił różne funkcje kierownicze, sprawując nadzór merytoryczny nad produkcją aparatury pomiarowej w Polsce.

W okresie pracy w Centrali MERY od 1972 r. był społecznie redaktorem biuletynu naukowo-technicznego MERA oraz od 1974 r. redaktorem działu „Nowości z Przemysłu Automatyki i Pomiarów” w czasopiśmie Pomiary Automatyka Kontrola. Od 1990 r. rozpoczął pracę w redakcji Pomiary Automatyka Kontrola jako redaktor ds. współpracy z przemysłem i doprowadził do reaktywowania upadającego czasopisma. W 1996 r. po odejściu całego zespołu redakcyjnego do nowo utworzonego miesięcznika PAR ponownie reaktywował czasopismo Pomiary Automatyka Kontrola, tworząc w 1997 r. od podstaw nowy zespół redakcyjny i nową Radę Programowo-Naukową. Dodatkowo w 1996 r. na prośbę Stowarzyszenia SIMP utworzył nowe czasopismo związane z ochroną środowiska pt. „Czystsza produkcja w Polsce” z redakcją w Warszawie i Gliwicach. W 2000 r. doprowadził do powstania samodzielnego wydawnictwa Pomiary Automatyka Kontrola i został jego dyrektorem. W latach 2000-2007 z Jego inicjatywy i przy czynnym współudziale wydawnictwo PAK wydało 8 książek o charakterze popularno - naukowym z dziedziny automatyki i pomiarów w tym takie pozycje, które wiążą się z wprowadzeniem w Polsce nowych technik:

1. Komputerowa Technika Pomiarowa,
2. Pomiary Termowizyjne,
3. Pomiary Światłowodowe,
4. Pomiary i regulacja dla potrzeb klimatu i mikroklimatu pomieszczeń.

Od stycznia 2007r. przeszedł na emeryturę przekazując całość spraw wydawnictwa PAK swojemu następcy z Politechniki Śląskiej w Gliwicach. Będąc na emeryturze, w 2008 r. na prośbę Fundacji Nauka dla Przemysłu i Środowiska wyraził zgodę na wykorzystanie Jego bogatych doświadczeń przy utworzeniu organu prasowego Fundacji. Udzielił pomocy intelektualnej przy tworzeniu nowego czasopisma PAKGOŚ ukierunkowanego na współpracę z przemysłem i uczelniami technicznymi w krajach Europy Środkowo-Wschodniej. Zmiana tytułu czasopisma na IAPGOŚ nastąpiła w 2011 roku. Od 2012 roku czasopismo wydaje Centrum Innowacji i Transferu Technologii w Lublinie. Mgr inż. T. Ustaborowicz w okresie swojej ponad 55-letniej pracy zawodowej był członkiem organizacji i stowarzyszeń naukowo technicznych m. in. Stowarzyszenia Elektryków Polskich (SEP), Stowarzyszenia Inżynierów i Techników Mechaników Polskich (SIMP), Polskiego Stowarzyszenia Pomiarów Automatyki i Robotyki (POLSPAR) (do chwili obecnej jest członkiem Zarządu Fundacji Nauka dla Przemysłu i Środowiska). Był wielokrotnie wyróżniany i nagradzany licznymi dyplomami, odznakami i odznaczeniami

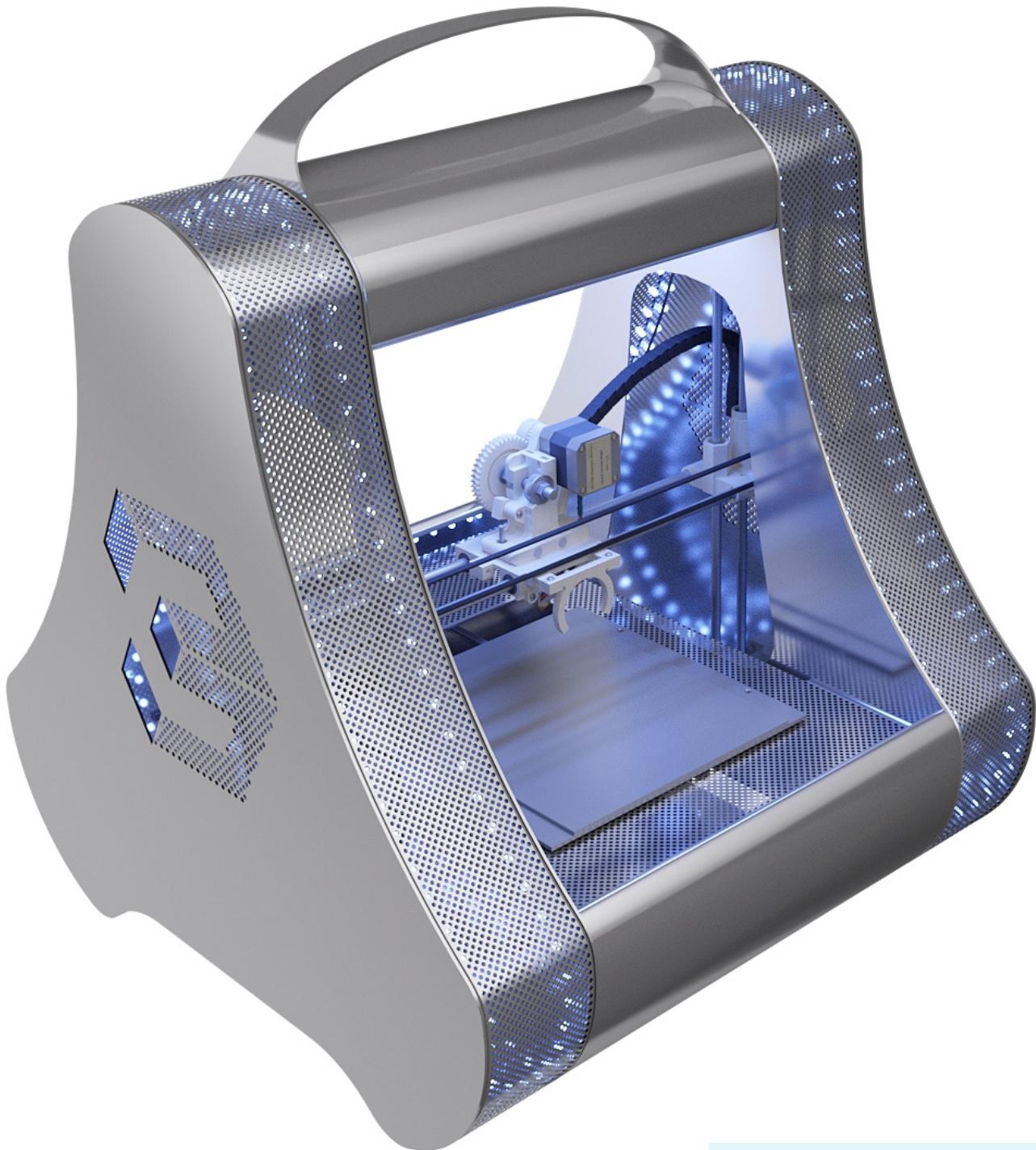
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długoletniej aktywnej pracy zawodowej oraz składają  
ŻYCZENIA ZDROWIA I POMYŚLNOŚCI w ŻYCIU OSOBISTYM**

Rada Programowo-Naukowa  
prof. W. Wójcik

Redakcja IAPGOŚ  
prof. J. Sikora

## DRUK 3D

Spółka 3dproto sp. z o.o. zajmuje się szeroko rozumianym drukiem 3d. Powstała W styczniu 2014 roku, a w swojej ofercie posiada już dwa modele drukarek 3d oraz dużą ilość wydruków na koncie. Zespół spółki poza technologią druku 3d w technologii FDM pracuje również nad technologiami skanowania 3d i w drugim kwartale 2014 roku zaprezentuje skaner z własnymi unikalnymi rozwiązaniami. Inżynierowie 3dproto sp z o.o. pracują nad wprowadzaniem innowacji w branży druku 3d, o czym świadczą przedstawiane rozwiązania.



Zdjęcie:

Zdjęcie przedstawia najnowszą drukarkę wychodzącą spod rąk inżynierów 3dproto sp. z o.o. Jej oficjalna premiera odbędzie się na przełomie marca i kwietnia. Drukarka zawiera innowacyjne dla branży druku 3d rozwiązania opracowane na podstawie badań oraz testów, a jej niecodzienny design z pewnością przyciągnie sporo zwolenników i entuzjastów druku 3d z Polski, a także spoza granicy.

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